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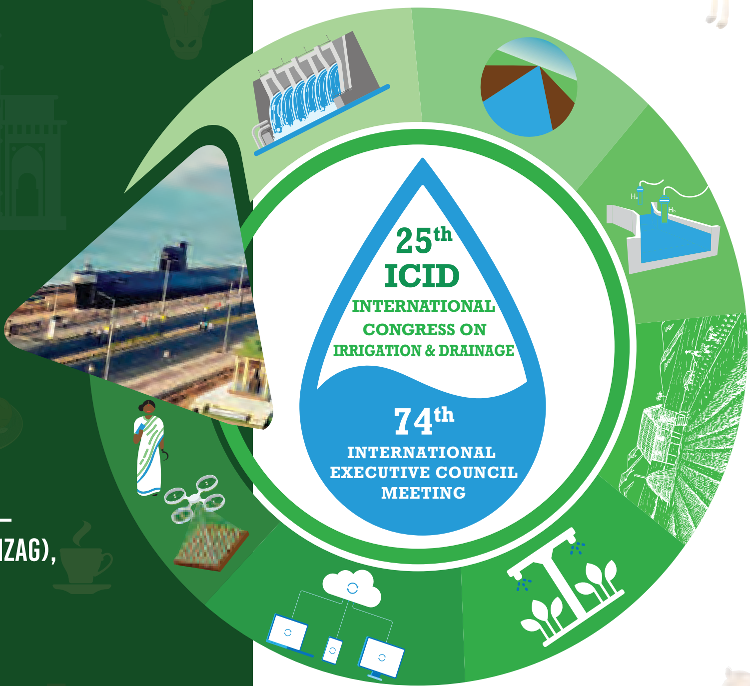

SIDE EVENT ON

MODERNIZATION OF IRRIGATION SYSTEMS

TACKLING WATER SCARCITY IN AGRICULTURE

LUTTER CONTRE LA PENURIE D'EAU DANS L'AGRICULTURE

INTERNATIONAL COMMISSION ON IRRIGATION AND DRAINAGE
COMMISSION INTERNATIONALE DES IRRIGATIONS ET DU DRAINAGE

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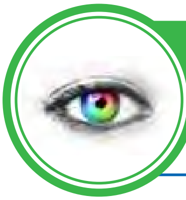
The International Commission on Irrigation and Drainage (ICID), established in 1950 is the leading scientific, technical and not-for-profit Non-Governmental Organization (NGO). The Commission through its network of professionals spread across more than a hundred countries, has facilitated sharing of experiences and transfer of water management technology for over six decades. ICID supports capacity development, stimulates research and innovation and strives to promote policies and programs to enhance sustainable development of irrigated agriculture through a comprehensive water management framework.



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- **E** Encourage Research and Support Development of Tools to Extend Innovation into Field
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Proceedings

Side Event on

Modernization of Irrigation Systems

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CONTENTS

THE EFFECT OF REMOTE CONTROL ULTRASONIC WATER METERS & VOLUME-BASED PRICING ON WATER USE EFFICIENCY

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ABSTRACT

As it is clearly seen in the recent global epidemic, war and economic crises, agricultural production is of strategic importance in order to meet the nutritional needs of living things, which are at the lowest level in the hierarchy of needs. Water and irrigation investments are the most important factors in increasing agricultural productivity and increasing the added value in the agricultural sector. Despite the proportional increase in other sectors in water use on a global scale, agriculture is still the largest user of water. 70% of the world's water resources are used in agriculture, 19% in industry and 11% for domestic purposes. In Turkey, these rates are currently 76% for agriculture and 24% for industry and domestic use. But in future projections, the share of irrigation (agriculture) is expected to decrease to 64%. The limited water resources and the increasing demand in all sectors make it necessary to use existing water resources in the most economical way. It is necessary for the environment to form a whole with its natural resources, the necessity of realizing all plans according to the philosophy of sustainable development, and climate change, which negatively affects water resources, and integrated management of water. The most important element in the management of water resources is to prevent losses during the transmission and distribution of water in agricultural irrigation, to reduce excess water demand in irrigated areas, to ensure effective use of water and to reduce risk. In this context, irrigation projects built by the General Directorate of State Hydraulic Works (DSI) are constructed as piped (closed) networks that minimize water loss, and open network irrigation facilities are converted into piped network irrigation facilities within the scope of modernization projects. However, constructing a piped network alone is not sufficient for effective use of water. In addition to using water-saving irrigation methods such as sprinkler and drip irrigation systems, irrigation water demands should be met by providing fair distribution in the desired time and amount in accordance with the existing water potential, the capacity of the irrigation system and the real needs. Automation applications in irrigation management, carried out within the framework of the use of technology in agriculture, can prevent outside intervention, especially in piped irrigation systems, and water can be supplied to the network in proportion to real needs. In this study, the results of Lora, Nb-IoT methods, remote control ultrasonic meter systems and volume-based water usage service fee tariff applications, which have started to be used in piped irrigation systems, were evaluated. According to the results of the monitoring and evaluation of the irrigation facilities in 2021, it has been observed that the highest water use efficiency can be achieved in irrigation areas where a water usage service fee tariff is applied on the basis of volume, and as a result, 45% water saving is achieved compared to the country average.

Keywords: water use efficiency, irrigation management, volume-based pricing, ultrasonic metering, remote monitoring.

1. Introduction

According to the projection made by the United Nations on the world population, the population is expected to reach 8.97 billion in 2050, and according to the projection made by the Turkish Statistical Institute, the population of Turkey is expected to reach approximately 95 million people. With the increase in the world population, the demand for clean and safe food is increasing rapidly. As can be clearly seen in the recent global epidemic, war and economic crises, agricultural production is of strategic importance in order to meet the nutritional needs of living beings, which are at the bottom of the Maslow's Hierarchy of Needs.

Water and irrigation investments are the most important factors in increasing agricultural productivity and increasing the added value in the agricultural sector. Despite the proportional increase in other sectors in water use on a global scale, agriculture is still the largest user of water. 70% of the world's water resources are used in agriculture, 19% in industry and 11% for domestic purposes (FAO Aquastat, 2016). In Turkey, these rates are currently 76% for agriculture and 24% industry and domestic use. But in future projections, the share of irrigation (agriculture) is expected to decrease to 64%.

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The limited water resources and the increasing demand in all sectors make it necessary to use existing water resources in the most economical way. It is necessary for the environment to form a whole with its natural resources, the necessity of realizing all plans according to the philosophy of sustainable development, and climate change, which negatively affects water resources, and integrated management of water. The most important element in the management of water resources is to prevent losses during the transmission and distribution of water in agricultural irrigation, to reduce excess water demand in irrigated areas, to ensure effective use of water and to reduce risk.

Ensuring effective use of limited water resources in the agricultural sector; it is a chain of activities from the water supply stage to the distribution and control of water, maintenance-repair and renewal of irrigation systems, monitoring and evaluation of irrigation systems, planning and development of irrigation projects, deciding on irrigation costs, resolving disputes between farmers, planning plant patterns and creating irrigation schedules.

Especially in recent years, it has been accepted as the basic policy to expand the piped irrigation systems in order to save irrigation water and to benefit more from the unit water in places where topographic and hydraulic conditions are suitable.

By the end of 2021; the rate of irrigation areas with piped irrigation network is 32%, the rate of canalized areas is 34%, and the rate of areas with open channels is 34% (Figure 1). It is foreseen that the piped network ratio will reach 45-50% in all irrigation projects with new projects and modernization of old irrigation systems in order to ensure effective irrigation management and significant water savings.

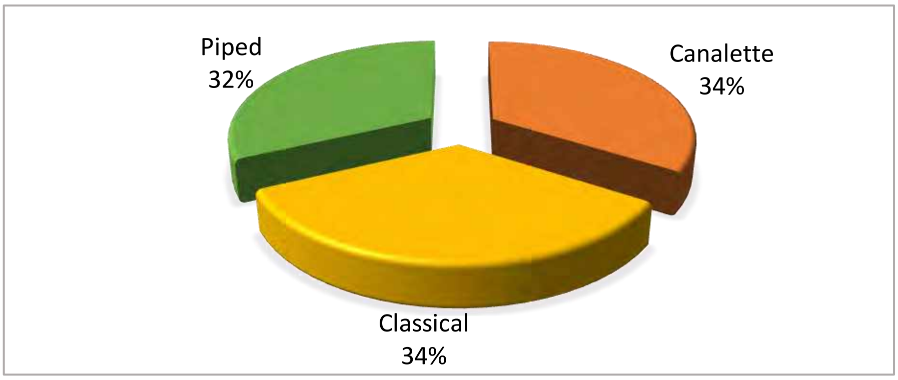

Figure 1. Current situation of the irrigation networks in Türkiye

In order to achieve the determined target, the needs of the facilities that cannot be met with maintenance works are met within the scope of the " Renovation Project" in order to continue the contribution of the irrigation facilities to the national economy, to ensure the continuity of the operation and maintenance activities and to save water.

The construction of 41 irrigation facilities serving an area of 37 thousand hectares has been completed and their transformation into a closed system has been ensured. Within the scope of the Renovation Project; construction, project design and planning works continue on an area of 1.3 million hectares.

In this context, special efforts are made to ensure that farmers prefer sprinkler or drip irrigation methods in their field applications. When we look at the results of monitoring and evaluation for many years, it is seen that there is an increase in water-saving irrigation methods due to factors such as the increase in piped irrigation systems by changing the irrigation infrastructure, the increase in the importance of effective use of water due to the droughts and the awareness of water users.

In 2003, when DSI made a policy change in the transition from open irrigation systems to pressurized pipe irrigation systems regarding irrigation systems, the area where drip irrigation system was applied was 1%, the area where sprinkler irrigation system was applied was 7%, and the area where surface irrigation methods were applied was 92%. 17, 23% and 60% respectively (Figure 2).

The graphic given below shows that constructing a piped network alone is not sufficient for effective use of water. In the remaining 60%, the use of irrigation methods such as sprinkler and drip irrigation with local energy supplements is encouraged in areas where the situation is suitable.

In addition to using water-saving irrigation methods such as sprinkler and drip irrigation required by the irrigation system, irrigation water demands; should be met by providing fair distribution in the desired time and amount in accordance with the existing water potential, the capacity of the irrigation system and the real needs.

An effective irrigation management can be achieved by measuring the water used at every level, completing on-farm improvement services and complying with water distribution programs. In this context, intensive efforts are being made to transform water measurement facilities into electronic systems that will allow central monitoring and evaluation in irrigation facilities that have been put into operation.

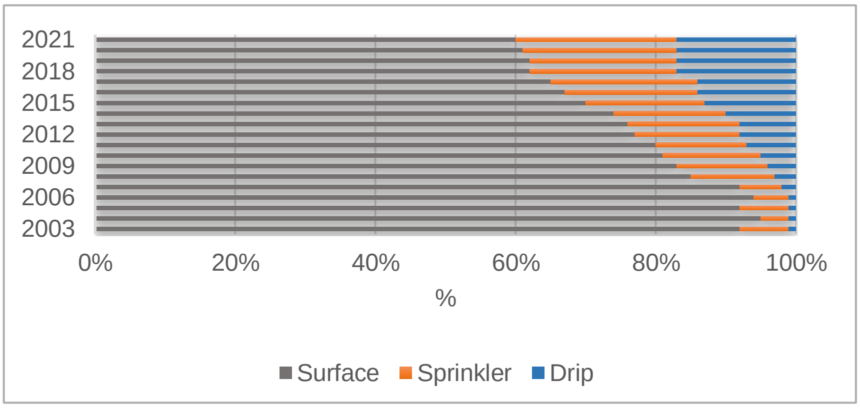

Figure 2. Irrigation methods applied in irrigated areas

With industry 4.0 (IoT), technologies that facilitate the work of the producer by increasing productivity, profit and quality in agricultural activities have advanced further and have begun to be called agriculture 4.0 in the agricultural sector. Automation applications in irrigation management, which are carried out within the framework of technology use activities in agriculture, can prevent outside intervention, especially in piped irrigation systems, and water can be supplied to the network in proportion to real needs.

2. Use of Technology in Irrigation to Ensure the Effective Use of Water

2.1 Water using by measurement

It is necessary to ensure the sustainable use of soil and water resources by protecting them from agricultural point of view, and the irrigation projects to be built in the current and future should be managed and operated effectively. In this context, the "Program for Enabling the Use of Water in Agriculture" has been implemented, and the aim of the program is; the activation of water use in agriculture by solving the problems that are caused or expected to be caused by climatic conditions and wrong and excessive water use throughout the country and on the basin basis.

In order to provide the expected economic and social benefit from the facilities and to manage them according to modern operating conditions, the flow and level changes coming to the storage facilities, the amount of water used in the irrigation network, given for purposes such as drinking water from the bottom spillway, irrigation, industry, should be measured. The measurements are of great importance in terms of providing data for the water distribution program studies to be carried out for the effective use of water and water saving, being the main data in the evaluation of the demands for the rehabilitation of the facilities, and guiding the integrated watershed management studies.

In this context, limnigraphs, flow meters, meters, etc. are supplied to the storage and irrigation facilities opened for operation. In order to monitor and evaluate the data obtained from the measurement facilities from a center, the installation procedures of a total of 832 electronic measurement facilities, including 484 limnigraphs and 348 flow meters, have been completed.

In order to monitor the water level in the storage facilities, the installation of an electronic lake observation station with central monitoring continues. From the established stations, the amount of water taken into the network in the irrigation facilities and the water levels of the storage facilities can be monitored instantly through the Gözbis application (Figure 3).

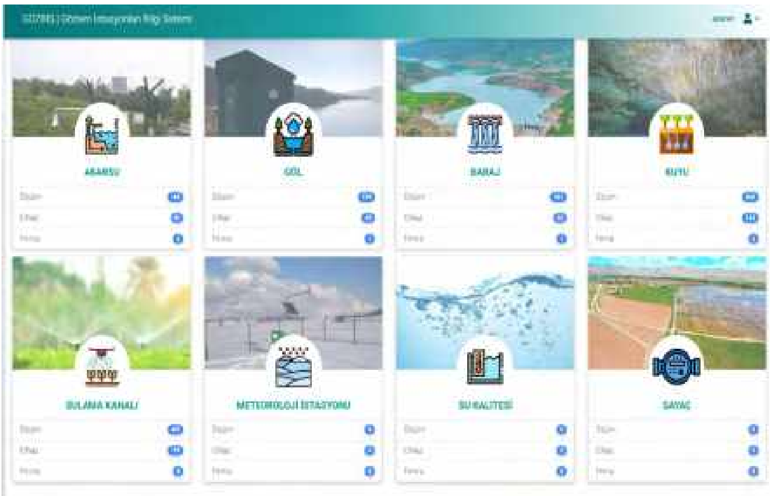

Figure 3. Observation Stations Information System

2.2. Use of Remotely Controlled Meters in Hydrants and Transition to Intelligent Irrigation Systems

It is of great importance to ensure that the existing water is used in irrigation areas within the program. In this context, basic principles such as fair sharing of water according to real needs, equality and reliability, effective use of the needed amount of water, prevention of unauthorized water intakes out of the program, and ensuring flow safety in the transmission and distribution of water are acted upon.

There is an integrated Lora module in the new generation ultrasonic irrigation meters installed in pressure-pipe irrigation facilities for the purpose of measuring and controlling the amount of water. Water usage is transferred to the gateway station at the preferred frequency and from there to the database via this module. In addition, with the pressure sensors installed on the system, the system pressure can be monitored over the application, and unusual changes in pressure values are determined and the problem is solved in a shorter time with the necessary intervention.

Data transfer frequency is determined as 1 hour in the specification for DSI irrigations. The meter number, water user information, irrigation start time (day – hour), irrigation end time (day – hour), amount of water used, amount of loss – illegal use etc. data is transferred to the database.

Through the software developed over the Lora application, commands such as starting and ending irrigation can be given to the meters from the water user association center, and the implementation of irrigation programs can be performed (Figure 4). It is allowed to use the specified amount of water in the time interval determined according to the irrigation program. Water users cannot irrigate out of the determined amount and time interval. At the end of the irrigation season, the water usage efficiency assessment of the irrigation area is completed by comparing the water usage amount in the flow meter at the beginning of the system and the total water usage information made in the meters in the irrigation area.

In addition to these studies, automation and decision support systems have been widely used for the better irrigation management. Especially with the automation applications in closed irrigation systems, outside intervention can be prevented and water can be supplied to the network to the extent of real needs.

Pilot irrigation automation projects are carried out in Bayırköy and Aydın Irrigation. Within the scope of the project, a remote-controlled meter system was installed on the hydrants. The irrigation time and the amount of water to be used in irrigation are determined by the water user organization according to the plant pattern, and the water user can start irrigation through the center or with the mobile phone application without going to the user's land (Figure 5-6).

On the other hand, the gate systems in the secondary and tertiary channels in Söke Irrigation, which has an open channel network, are remotely controlled and adjusted by automation.

Figure 4. Ultrasonic Irrigation Meter Central Control Screen

Figure 5. Automation Equipment and Mobile Application

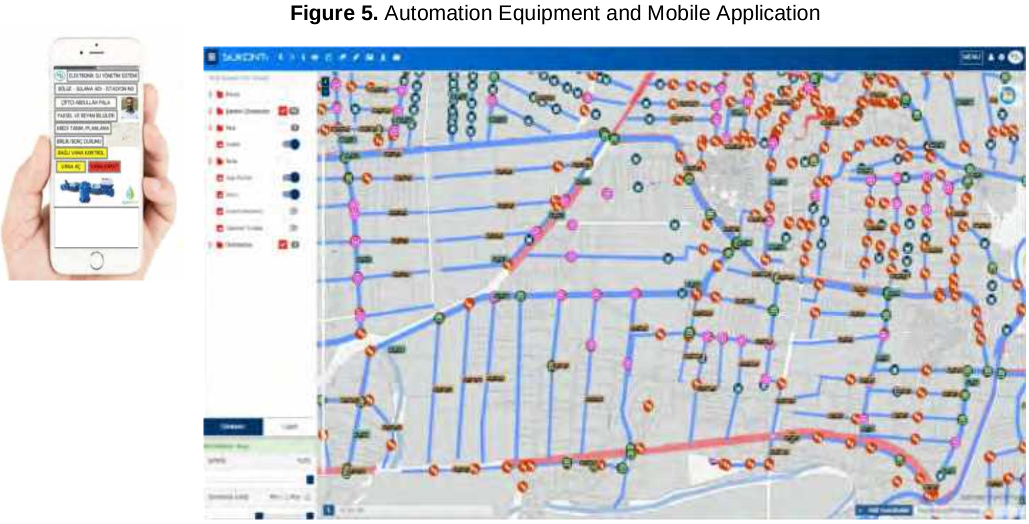

Figure 6. Automation Centre Control Screen

These studies have been carried forward in İmamoğlu Irrigation. Again, depending on the central control and management, in addition to the system where the users can irrigate remotely, the soil moisture sensors and the data received from the multi-parameter meteorology station are evaluated to see if there is a water need. The groundwater level is monitored with 3 parameters and the pressure control of the network is instantaneously monitored from the pressure sensors.

3. THE EFFECT OF VOLUME-BASED PRICING ON WATER USE EFFICIENCY

According to 2021 monitoring and evaluation results; irrigation efficiency in Turkey is 50%, water usage per unit area is 9 515 m3/ha; in piped irrigation networks with meters, irrigation efficiency is 65%, water usage per unit area is 7 299 m3/ha; in irrigation facilities where a volume-based (TL/m³) water usage service fee tariff is applied, irrigation efficiency is 88%, water usage per unit area is 5 173 m3/ha was calculated (Figure 7).

Therefore, it has been determined that 24% water savings are achieved in closed irrigation systems compared to the average, and 46% water savings are achieved in irrigation facilities that charge on the basis of volume.

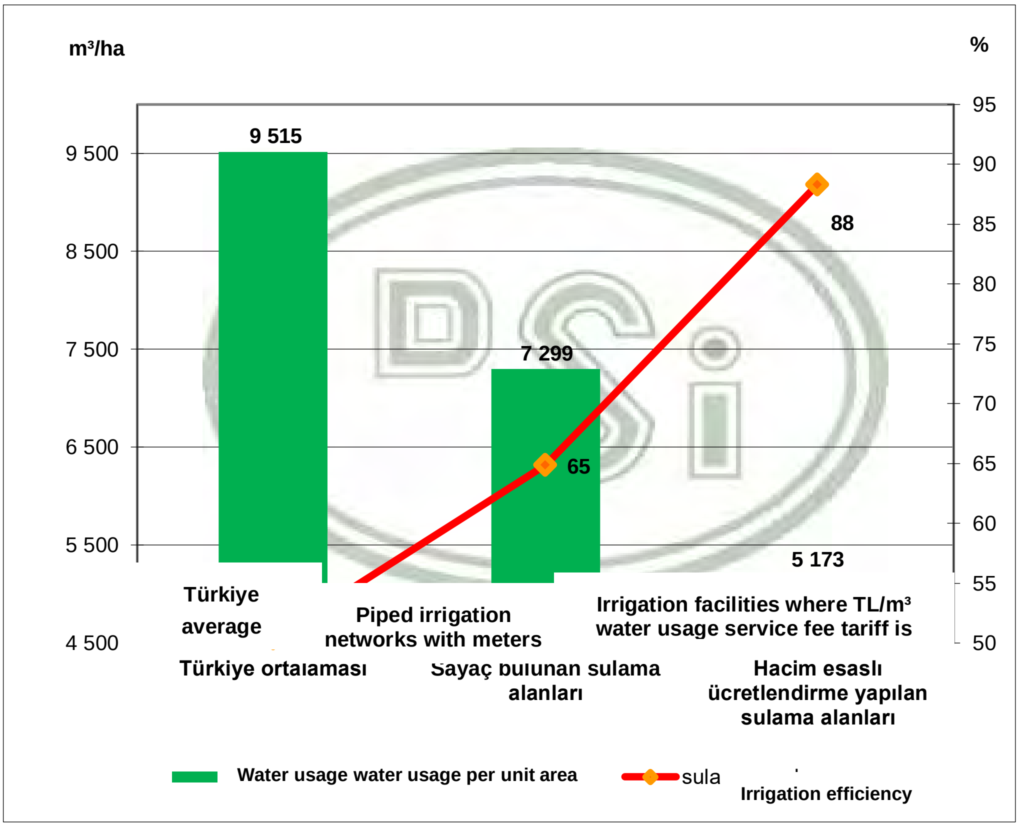

Figure 7. Water Usage Effectiveness in 2021

On the other hand, in order to prevent the use of water more than needed in agriculture, a pilot study was initiated to charge the water usage service fee according to the amount of water used. In volume-based pricing, while the cubic meter price is fixed, the price is applied by increasing or decreasing in each unit water increase or decrease used in the gradual service fee application. Thus, the water usage service fee is applied with an approach that rewards more when less water is used, or punishes more when more water is used, encouraging the use of water as much as the plant needs.

With this pilot study, water users save water by switching to modern irrigation methods in order to consume less water per unit area, reduce operating and maintenance costs, protect water and soil resources, reduce energy costs, especially in pumped irrigation, as less water will be used, thus enabling farmers to benefit from irrigation services even more cheaply.

4. CONCLUSION AND RECOMMENDATIONS

In this study, the results of Lora, Nb-IoT methods, remote control ultrasonic meter systems and volume-based water usage service fee tariff applications, which have started to be used in piped irrigation systems, were evaluated.

When we look at the long term results of monitoring and evaluation for irrigation facilities, it is seen that there is an increase in water-saving irrigation methods due to factors such as the increase in piped irrigation systems by changing the irrigation infrastructure.

According to the results of the monitoring and evaluation of the irrigation facilities in 2021, it has been observed that the highest water use efficiency can be achieved in the irrigation areas where the water usage service fee tariff is applied on the basis of volume, and as a result, 46% water saving is achieved compared to the country average.

However, the fact that surface irrigation methods continue to be used despite the appropriate irrigation infrastructure shows that the construction of a piped network alone is not sufficient for effective use of water. In addition to structural measures such as encouraging the use of water-saving irrigation methods by subsidies, non-structural measures such as volume-based and gradual pricing are inevitable.

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FINANCING MODERNIZATION OF IRRIGATION SYSTEMS:

Background Paper

Preface

This paper has been prepared by the World Bank's Water Global Practice for the International Commission on Irrigation & Drainage (ICID) for the World Irrigation Forum (WIF4) 2023 to be held April 16-22, 2023 in Beijing, China. The paper was prepared by Christopher Ward, IJsbrand H. de Jong, Francois Onimus, Pieter Waalewijn, Svetlana Valieva, Ruyi Li, Stuti Sharma, Remi Trier, Palak Sharma, Eeman Amjad, and Amal Talbi.

The aim of the paper is to document the range of financing available for the modernization of irrigation and drainage, to evaluate experience, and to provide some pointers for the further development of this financing.

In the paper, the term 'modernization' is used to cover both improvement of existing irrigated areas and practices and investment in extension of the irrigated area.

Principal sources of information

In addition to some new research, the paper is primarily based on a number of excellent existing studies, notably papers by OECD, the material prepared for the 2021 FAO Roundtable on Financing the Sustainable Use of Water for Agriculture, and several recent World Bank studies.

Key amongst the OECD papers were Financing water: Investing in Sustainable Growth (2015); Making Blended Finance Work (2019); The role of intermediaries to facilitate water-related investment (2020); and Financing a Water Secure Future (2020).

FAO papers which were of great value included: Helen Laubenstein's excellent 2021 paper Opportunities for investments in agricultural water to contribute to a green and resilient recovery and mobilize commercial finance; and The case for action on financing agricultural water by Colette Ashley and Dr Guillaume Gruere (2021).

Some recent World Bank publications also provided much material, including the 2018 (draft unpublished) report Sustainable Irrigation Performance under Changing Conditions; the 2020 paper Governance in Irrigation and Drainage: Concepts, Cases, and Action-Oriented Approaches—A Practitioner's Resource; the 2021 Farmer-led Irrigation Development Guide: A what, why and how-to for intervention design); the handbook on Innovation and Modernization in Irrigation and Drainage (forthcoming); the 2022 Enabling Private Finance for Irrigation (forthcoming); and the 2022 FLID update Reflections on Farmer-led Irrigation Development (FLID) across Africa.

Overview

Modernization of irrigation is driven by the rising demand for food and fiber from an increasingly constrained land and water resource base. New technology and institutional mechanisms and more entrepreneurial and market-oriented approaches are enabling and incentivizing farmers to modernize their irrigated operations to achieve more output and value and higher incomes.

Modernization requires investment – and financing. Historically, governments financed much irrigation investment but recent trends are towards less and more efficient and targeted public support. Governments are likely to focus more on investing in basin infrastructure and natural resource management, on public goods and public policy objectives, and on correcting market failure. Workable models that leverage private finance like PPP and blended finance have been slow to emerge but are likely to become progressively more common.

Private finance for irrigation and modernization has grown considerably in recent years with new instruments such as low entry cost models – rentals, leasing, pay-per-use – and forms of consumer credit. Guarantees and insurance are also being used to underwrite finance for modernization. New sources of finance include water investment funds, ecosystem support financing and green bonds.

These new instruments and sources have helped smallholders to invest in affordable modern on-farm technology. Recent emphasis on 'farmer-led irrigation development' (FLID) is expanding access to modernization for very resource poor farmers.

If modernization is to achieve its potential – and if all farmers are to have access to its benefits – modernization investments need to improve their poor 'bankability'. On the supply side, this means helping the development of financial markets that are adapted to the need, including new providers, new instruments, and new sources. Support is needed too to ensure that modernization investments are profitable and bankable: this may require investments in basin infrastructure or the strengthening of value chains. Farmers also need access to the knowledge required to prepare 'bankable' proposals. A key new tool is financial technology (Fintech) which uses digital technologies to improve financial services – and can also integrate irrigation operations with credit appraisals and financial transactions.

Along with support to enterprise, safeguards are essential. Modernization must take place 'responsibly', within a sustainable environmental management framework. Public financing remains vital, bit it needs to be targeted and 'smart'. All stakeholders need to work together to develop a strategic approach to financing modernizati

Summary

1. Introduction: The imperative of irrigation modernization

The need for more and better irrigation and drainage

There are many reasons why modernization is an imperative for irrigation and drainage (I&D). First, with the world's population increasing, there is an ever-rising demand for food and fiber, In addition, with rising living standards and urbanization, there are changes in dietary patterns, notably towards more fresh fruits and vegetables. These changes on the demand side create growing incentives for farmers to change their cropping patterns and, in the context of increasing water scarcity, to invest in efficient 'modern' irrigation.

Second, with climate change, temperatures are rising, water resources are dwindling and becoming less certain, and climate-related extreme events such as droughts and floods are on the rise. Irrigation provides a more stable and controllable access to water and is also more resilient to the impact of temperature.[1] There are strong incentives for existing irrigated farmers to improve their access to water and to make the best use of it on-farm, and for rainfed farmers to transition to at least partly irrigated production, More generally, poor farmers need to modernize their water management in order to rise out of the low productivity trap that keeps them poor.

In addition, pressure on natural resources is driving moves towards the most efficient and sustainable irrigation techniques to make the best use of increasingly limited land and water resources, and to reduce negative effects of irrigation on the environment, including soil and water resources.

At the same time, the irrigation sector is changing towards more entrepreneurial and market-oriented approaches with smaller and better-targeted public sector intervention. In parallel, purely private irrigation has expanded enormously, notably with the rapid development of groundwater. This has vastly increased irrigated output and, through precision irrigation, boosted water productivity – but has been accompanied by significant depletion and deterioration of the resource.[2] The push to modernize I&D is helped by the abundance of new technology that can boost irrigation efficiency (both in terms of conveyance and on-farm application of water) and reduce the costs of irrigation service.

What is modernization – and why is its financing important?

'More for less' is the opportunity and challenge for irrigation today**.** Modernization essentially consists of a range of options to obtain more value from less water. Incentives to modernization are strong at all levels. For irrigating farmers, modernization promises higher incomes. For systems and system managers, it allows a better and lower cost water service delivery that responds to farmer needs. And at government level, modernization can realize national objectives of economic growth, food security, and natural resource use efficiency, and can also ease the strain on fiscal resources.

Modernization is essential to fulfil the potential of irrigation – but it needs financing. Because modernization requires considerable investment, the financing of irrigation modernization is of capital importance.

2. Who finances irrigation and irrigation modernization?

Levels and character of public finance of irrigation and irrigation modernization

Historically, finance for irrigation has predominantly come from public sources – and this remains the case for ongoing irrigation modernization efforts. Global levels of public financing for agriculture-related water resources development and irrigation are high – in 2019, public finance for 'agricultural water' worldwide totaled $42 billion. This public financing covered both irrigation investment (70 percent) and investment in the broader basin to mobilize or protect agricultural water resources. Little of this public finance is recovered from irrigators.[3]

The balance of investment financed from public sources is very different between developed and developing countries. Developed countries mainly finance basin infrastructure and natural resource management. In developing countries, the lion's share goes directly towards financing of irrigation infrastructure. The difference

[1] See, for example: https://openknowledge.worldbank.org/handle/10986/34498

[2] See Kuper M. et al. (2016). "Liberation or Anarchy? The Janus Nature of Groundwater Use on North Africa's New Irrigation Frontiers". In: Jakeman A.J., Barreteau O., Hunt R.J., Rinaudo JD., Ross A. (eds) Integrated Groundwater Management. Springer, Cham. https://doi.org/10.1007/978-3-319-23576-9_23 Also, Tushaar Shah (2008) Taming the Anarchy: Groundwater Governance in South Asia.

[3] For a sample of 20 developing countries, farmers do not pay for CAPEX at all. In nine of the 13 countries where OPEX data are available, farmers do need to contribute to OPEX. In total, 94 percent of total irrigation spending is not recouped through charges to farmers. Source: the global survey on irrigation financing and subsidies, conducted in 2022 by the World Bank Water GP Global Unit and the Sustainable Development (SD) Vice Presidency.

reflects the fact that in developed countries, the financing of irrigation infrastructure and on-farm investment is largely an area for private investment - the responsibility of the farmers. This approach is consistent with water sector policies in developed countries that farmers should face the true cost of irrigation service in order to improve allocative efficiency of water resources. By contrast, in developing countries, irrigation financing has been used in pursuit of multiple other objectives such as food security and poverty reduction. In addition, significant public financing in developing countries – particularly China and India - went to 'producer support', largely as subsidies for water or electricity.

Public investment in modernizing irrigation

Government remains, far and away, the biggest source of financing for modernization for off-farm infrastructure and large scale schemes. However, in recent years, new cost recovery measures have begun to increase accountability and reduce the fiscal burden of public financing.

One form of public support in irrigation modernization has been the public private partnership (PPP). Typically, this has taken the form of either management, operation and maintenance (MOM) contracts or infrastructure concessions. To date, experience has been limited – and not always successful. However, as more experience is gained, new formulations are being devised to sharpen incentives and rebalance risk-sharing.

Public irrigation investment in many countries has also supported modernization for smallholders on both large scale public schemes and small scale collective and individual schemes. A notable example of public support to very small scale individual and communal irrigation in Niger used matching grants to support the modernization of thousands of smallholder irrigation operations and also to build sustainable institutions for further development and financing of irrigation modernization.

Development assistance for modernization

Development assistance for irrigation is relatively limited compared to total government financing ($1 billion vs. $40 billion annually) but it provides a useful incubator for innovation. In recent years modernization has become the main objective of irrigation projects supported by international financial institutions (IFIs)-, which have progressively moved away from an early over-emphasis on canal lining towards a broad array of modernization approaches. As a result, IFI projects provide a rich source of knowledge and innovation on how to modernize.

Finance for farm-level irrigation and modernization

There is significant demand for on-farm modernization – but limited access to finance. Historically, finance for irrigation at farmer level has been on a small scale and largely informal. In recent years, new technology and new markets have stimulated farmer interest in modernization and much of the 'modern' technology is relatively affordable, particularly on-farm. However, self-financing by farmers still predominates, and even low cost on-farm modernization is out of the reach of many farmers.

Experience has shown that financing can provide a critical bridge across the affordability gap and new approaches are being tried out. These include approaches like communal service provision, and matching grants to develop provision of financing by the private sector. A number of private and not-for-profit agencies have emerged to help finance small farmer modernization and there have been efforts by governments to help develop sources of finance for these farmers. However, results are so far limited and have sometimes been skewed towards those who are already better off.

Farmer-led Irrigation Development (FLID): financing small scale and individual private irrigation

In recent years, there has been a revival of the focus on farmer-led irrigation development (FLID). This focus on 'FLID' has identified as a target group amongst smallholder irrigators those extremely resource poor farmers whose only route out of poverty is to improve water management in their farming operations but who lack access to the knowledge, markets and finance to bring about these changes. A number of countries and programs are supporting ways to increase access by this target group to irrigation (and to broader agricultural water management) - a good example is Rwanda's long-standing and successful FLID financing program.

Since 2018, the World Bank and partners have developed a special program to support FLID. Early results from Sub-Saharan Africa are promising but underline the need to ensure equity and inclusion and that FLID takes place within a supportive governance and regulatory framework while ensuring sustainable use of natural resources.

3. New ways to finance irrigation modernization

New financing instruments

Blended finance to leverage private capital for modernization could potentially play a major role in scaling up commercial investment. Blended finance brings together public and private finance in risk sharing arrangements. However, although blended finance facilities for infrastructure projects have multiplied in recent years, they have had only limited impact in the irrigation sector. One area where blended finance has had some success in irrigation is in encouraging private providers to enter the market for retail financing, including both financial service providers and provider of irrigation services and equipment etc.

Low cost entry models include rentals, leasing, and pay-per-use ways of accessing equipment and services. Finance for modernization may also be leveraged through value chain partners, for example, Business-to-Business (B2B) and Business-to-Customer (B2C) arrangements. These partners include last-mile service providers and manufacturers, and retailers of irrigation equipment (e.g., solar pumps, micro-irrigation equipment, etc.).These businesses can sell, lease, or rent irrigation equipment and products, and provide pre-and after sale services. They may also simply provide consumer credit, which is now well established across Asia, particularly in India. The trusted relation between trader and out grower can be used to underwrite lending for irrigation investment.

Supporting instruments – guarantees and insurance

Guarantees and insurance can be used to underwrite lending and risk management for modernization. Guarantees can support the provision of credit either at the level of a major investment – as with MIGA guarantees - or at the level of credit to irrigators, where there is successful experience, for example in Tanzania. In order to reduce lenders' risks, farmers may be able to buy insurance.

New sources of funds for irrigation modernization

Dedicated water investment funds are financing irrigation projects around the world. Relief projects and recovery funds have also been set up, particularly in the wake of the COVID-19 crisis. Ecosystem support funds represent collective investment vehicles that allow stakeholders to pool capital to finance improved water management or to pay for ecosystem services. Despite the complex nature of these mechanisms, they have largely proven effective in improving natural resource outcomes, including for agricultural water management. At a national scale, China has financed a massive 'ecological compensation' program which includes many investments in agricultural water management. Green bonds are designated bonds intended to encourage sustainability and to support climate-related or other types of special environmental projects. Globally, green bonds are currently mobilizing $270 billion a year, with China and India – and the World Bank - amongst the leaders. Green bonds have helped finance a range of irrigation modernization programs.

4. Five essentials needed to move forward

The need for more investment in modernization is pressing and, to move forward, work is needed on five essential points described below.

Improving access to finance

Faced with the inherent challenges of financing irrigation, private financiers been so slow to meet the market demand. The specific character of irrigation makes it a difficult sector to finance. From the financiers' viewpoint, investing in irrigation carries high risk and has a doubtful risk-to-return profile. Investments also tend to be relatively remote and often small. In the case of financing larger scale irrigation infrastructure, there are problems in ensuring adequate cash flow because of poor levels of cost recovery. Thus, irrigation investments, both large and small, typically have poor 'bankability'.

The implications are that public support is essential both to improve access and achieve public policy objectives for food security and sustainable resource management. The main challenges are to make public support to financing efficient – and how to minimize – and progressively reduce - the burden on the public purse. To that end, fiscal resources from misdirected subsidies may be freed up to finance these changes.

An approach that combines more than one public funding mechanism with other interventions is usually needed. For example:

- to support emerging financial markets or expand them into underserved areas; a combination of upfront grants and results-based financing can be applied.
- If farmers lack access to working capital financing but are otherwise close to being able to meet the lender's requirements, credit lines and risk mitigation can be considered.
- Where market-based solutions are not viable, demand-side tactical and targeted subsidies can mitigate risks, or quite simply outright innovative public procurement and service delivery contracts with a view to building market viability.

Developing new providers, new instruments, and new sources

In supporting the development of new providers, the challenge is to align the business models and incentives between public and commercial actors. Several governments are having some success in developing financial markets, for example in Rwanda. Intermediaries can also play an important role in broadening access to credit and in minimizing transaction costs. Locally-based savings and credit cooperatives (SACCOs), projects, or NGOs may play this role and can integrate financing options within broader support to irrigation modernization and agricultural development.

New and emerging instruments with have potential for scaling up.. Public funds, which have historically provided the lion's share of irrigation financing, can play a very significant role in leveraging private finance. In particular, applying blended finance to irrigation, although limited to date, holds promise. There is considerable scope to develop low cost entry models such as rentals, leasing, and pay-per-use and to leverage finance through value chain partners, with Business-to-Business (B2B) and Business-to-Customer (B2C) arrangements and consumer credit. The trusted relation between trader and out grower can be used to underwrite lending for irrigation investment. There is also scope to extend the use **of g**uarantees and insurance. One powerful de-risking method is to work with farmer organizations in taking an integrated value chain approach, thereby integrating access to finance within broader market-based development.

There is potential also to develop new sources of finance. There is a growing number of investors and agencies interested in financing sustainable agriculture, including irrigation, and there is potential for financing from the Paris Accords and the subsequent agreements at Glasgow.

Ensuring that the investments are profitable and bankable

Making investments in irrigation modernization credit-worthy requires the promise of profitability and income streams. This may require investment beyond infrastructure or cultivation, for example in transport or access to markets along the agricultural value chain. It may also require devising of income streams for non-market goods resulting from agricultural production.

In addition, making profitable and bankable investments in modernization requires knowledge – for example, on what is the best investment and how can it best be acquired, financed, and managed. Knowledge support networks for irrigation need to be set up or strengthened specifically to help farmers prepare bankable investments in irrigation modernization.

Financial technology (Fintech) and digital solutions

Use of Fintech represents a major opportunity to overcome the historical constraints of access to financial services for the poor. Fintech - the use of digital technologies to improve financial services – has become a powerful mechanism, enabled by high uptake of smartphones. Fintech can integrate irrigation operations with financial transactions. Fintech platforms can also be used for credit assessment and appraisals. A notable example is from Uganda, where an app 'IrriTrack' is used to develop, finance and implement individual irrigation modernization plans.

Ensuring responsible investment in modernization

It is essential to ensure that privately financed, privately executed, and privately owned and managed investments in modernization are made responsibly because of the negative externalities and risks of harm to public interests. There is, thus, a role for government in setting and implementing a legal and regulatory framework that ensures sustainable water resources management and environmental husbandry. Private investment in agricultural water also needs to fit within basin management plans, agricultural development plans, etc.

5. Looking ahead: increasing the provision of finance for irrigation modernization

Towards a new role for government in financing irrigation modernization

Historically public finance and international transfers have predominated – but there have been significant weaknesses as a result. High levels of public subsidies have produced a huge and lingering burden on the public purse. Poorly directed subsidies have also distorted market incentives, crowded out private finance, and leveraged scant levels of private capital. In addition, at the country or basin scale, extremely high levels of subsidies have led to expansion of irrigation that is uneconomic and detrimental to the land and water resources used in food production processes.

Essentially, the role of government needs to change. Governments need to invest principally in public goods and basin-level infrastructure and in supporting the viability of farming systems in line with specific (targeted) economic and social objectives, while facilitating the private sector and farmers to invest in irrigation infrastructure and its operation.

Within this changed role of government, there is clearly a case for repurposed public financing - and of subsidies. Public investment in modernization needs to be 'smart' and targeted to enable provision of public goods or advance public policy goals such as equity, poverty reduction, and inclusion (including gender inclusion), or to correct market distortions or failures in financial or product markets. Subsidies may, for example, be aimed at correcting market failures in financial or product markets or at promoting environmentally sustainable cropping patterns and irrigation and production practices. In addition, there is a clear role for governments in R&D, institutional development and all aspects of training and capacity building. In more developed economies, public financing is already focused on these areas and developing economies are beginning to move in this direction.

What are the conditions to increase provision of finance for irrigation modernization?

Governments can ensure a supportive enabling environment along with targeted and predictable patterns of public investment. Within this framework, they can work with all stakeholders to develop a strategic approach to financing modernization. Governments can work together with other stakeholders to strengthen the enabling environment for facilitating investments by developing clear policies governing irrigation development within broader natural resource management. Governments also need to have clear policies on how irrigation modernization is financed, and a smart and consistent public financing approach with a framework that supports private investment in irrigation. With these policies and frameworks in place, governments can develop a strategic financing approach in partnership with all stakeholders.

Chapter One – Introduction: The imperative of irrigation modernization

1.1 The need for more and better irrigation

Worldwide, there is ever increasing demand for food and fiber, together with changes in dietary patterns towards more fresh fruits and vegetables.

Future food demand is set to double between 2020 and 2050, with the world's population projected to reach 9.7 billion by 2050 (World Bank 2019, FAO 2017a). This increase in global food demand is associated with a shift in diets associated with higher incomes and living standards as well as increasing urbanization. Future diets will include more fruits and vegetables. (Molden, Frenken, et al. 2007).

These changes on the demand side create growing incentives for farmers to change their cropping patterns and, in the context of increasing water scarcity, to invest in efficient 'modern' irrigation.

With this growth in demand for higher value crops, but also in the context of increasingly scarce and expensive water resources, farmers are switching their cropping patterns and are investing in more efficient 'modern' irrigation that helps to give more '$ per drop' and higher incomes. This investment require financing.

Also, on the supply side, there is a strong incentive for rainfed farmers to transition to at least partly irrigated production.

Climate change is altering rainfall patterns and leading to warming, while droughts are affecting rainfed production, thereby creating a growing demand to convert rainfed lands to irrigated, or at least to employ supplementary irrigation.

More generally, irrigation modernization can help lift smallholder farmers out of the low productivity trap that keeps them poor.

As developing economies move progressively towards middle income status, there is a growing gap between urban and rural incomes. In Vietnam's Mekong Delta region, for example, irrigated plots are small and typical household incomes from farming are no more than $1,000 a year, set against nationwide average incomes of more than $5,000. Hundreds of millions of irrigated farmers, especially across Asia, are caught in this poverty trap. Modernization provides hope that farm production can diversify and farm incomes can grow.

Climate change and other pressures on natural resources and the environment are also driving the need to modernize irrigation infrastructure, practice, and services.

With climate change, temperatures are rising, water resources are dwindling and becoming less certain, and climate-related extreme events such as droughts and floods are on the rise. Irrigation provides a more stable and controllable access to water and is also more resilient to the impact of temperature.[4] There are strong incentives for existing irrigated farmers to improve their access to water and to make the best use of it on-farm, and for rainfed farmers to transition to at least partly irrigated production, More generally, pressure on natural resources is driving moves towards the most efficient and sustainable irrigation techniques to make the best use of increasingly limited land and water resources, and to reduce negative effects of irrigation on the environment,

[4] See, for example: https://openknowledge.worldbank.org/handle/10986/34498.

including soil and water resources. These pressures combine with complementary pressures and opportunities within the irrigation sector to promote entrepreneurial and market approaches and to favor less and better-targeted public interventions.

In recent years the former dominance of 'top down' and 'command and control' approaches to irrigation development and management has lessened. For two decades, moves to modernize irrigation service provision have put farmers and farmer-led institutions more in control and started to bring private sector efficiency and financing into irrigation.

In tandem, the role of government in investment in infrastructure and its management has diminished. Governments have supported modernization of both infrastructure and institutions in order to improve outcomes but also to reduce the fiscal burden, especially by limiting and better targeting subsidies, transferring management, operation and maintenance (MOM) responsibility to farmers, and moving towards higher levels of cost recovery of irrigation service provision. Modernization of infrastructure serving existing irrigated areas as well as the development of new irrigated areas – can serve a range of public policy objectives.

Investment and management measures to modernize irrigation are primarily designed to increase water efficiency (maximum water conveyed to plant roots) and productivity (maximum $ per drop) and so boost value added and increase farmer and national income. However, modernization can also achieve broader environmental and water security objectives such as improving watershed management, restoring environmental flows, flood control through drainage, and reducing pollution and waterlogging. Modernization can also help increase resilience to changing weather patterns and disasters and support water (re)allocation amongst competing water uses (for example, releasing water from irrigation for urban uses).

On the supply side, the availability of abundant new technology can boost irrigation efficiency., This includes the panoply of on-farm and off-farm technology discussed in the handbook on *Innovation and Modernization in Irrigation and Drainage (World Bank, forthcoming).* At the I&D system level, a wide range of technologies combined with appropriate changes in their management and governance (through relevant) institutions has developed with the overriding objective of improving water service delivery to farmers.

Much new on-farm technology has become available and is relatively accessible even for smallholders and a vibrant industry of manufacturers and suppliers has developed in most countries, predominantly in the private sector. More recently, the technological revolutions and artificial intelligence have begun to support farming decision making.[5] [Source: Waalewijn et al 2019]

1.2 What is modernization – and what are the incentives at farmer, system, and government levels[6]

'More for less' – the opportunity and challenge for irrigation today

Modernization is essentially a range of options to get more value from less water – and incentives are strong at all levels.

Irrigation clearly faces a massive challenge – to respond to the opportunity of the rapid change in water demand patterns from constrained and possibly diminishing water resources and to other changing conditions, including competition for water, climate change, demand for better quality service etc. Modernization essentially represents a range of technical and management options to respond to these challenges. Incentives for modernization are strong at all levels – at the level of farmers, of systems and their operators, and at government policy level.

For irrigating farmers, if done properly, modernization promises higher incomes. Reduction in costs, improvements in yield along with the opportunity to participate in new or improved agricultural value chains gives farmers the ability to increase incomes. Modernization facilitates this increase by providing a more reliable, flexible (on-demand), and affordable water delivery service along with on-farm irrigation technology and agricultural practices that maximize farm income and the sustainability of farming operations.

The basic challenge at the system level is to deliver a water service that responds to farmers' needs. I&D systems often fall short of their design objectives of reliable water deliveries to farmers (and removal of drainage). A few I&D schemes are able to respond to changes in the patterns of farmers' demand for more reliable and flexible service that would enable farmers to improve their irrigation techniques and cropping patterns.

Modernization of hydraulic infrastructure and equipment along with good management and governance offer solutions to improve the reliability and efficiency of water service delivery to farmers. Modernization can also strengthen systems' long-term resilience and reduce negative environmental and social externalities, such as

[5] For example, autonomous farm machinery, and remote sensing for real-time crop management are already established and evolving quickly. Technical support services, drones, open-access satellite imagery, evapotranspiration datasets, and integrated expert diagnostic systems for irrigation management are now expanding from developed to developing countries. Mobile (GSM)- enabled supervisory control and data acquisition (SCADA) systems, which are rapidly becoming cheaper and simpler, can be easily installed for flow measurement and monitoring in canal and groundwater systems.

[6] This section is based on material from World Bank 2022a.

Resource depletion or pollution, by improving resource use efficiency.

At government level, modernization can realize national objectives of economic growth, food security, and resource use efficiency, and can also ease the burden of providing I&D services to farmers on fiscal resources. For governments, irrigation modernization enables a more efficient, productive, and profitable irrigated agriculture sector, strengthens water security by making the best use of limited water resources in irrigation, and can result in a more profitable irrigation sector, less dependent on government support. The resulting potential increases in farmers' productivity also provide a positive boost to a country's gross domestic product (GDP).

Chapter Two – Who finances irrigation and irrigation modernization?

2.1 Historically, finance for irrigation has been predominantly drawn from public sources – and this remains the case for irrigation modernization

2.1.1 Global levels of public financing for agriculture-related water development and irrigation

Over the past two decades, there has been an increase followed by a decline in public financing of 'agricultural water' provision, with $42 billion invested in the most recent year studied (2019). Although estimates of aggregate financing of 'agricultural water' worldwide are hard to come by, one study (OECD 2020b) compiled estimates for 54 countries (41 OECD countries and 13 large emerging economies) that showed a doubling from the year 2000 (at $25.9 billion annually on average) up to 2011 ($54.2 billion) and then a subsequent dip to $41.6 billion in 2019 – see *Figure 1: Total water related agriculture support*.[7] This public financing covered both irrigation investment (70 percent) and investment in the broader basin to mobilize or protect agricultural water resources.

Some 70 percent of this public support to agricultural water delivery was through public financing of I&D infrastructure. The balance went to associated investments in the basin. Of this, 18 percent was invested in basin-level infrastructure related to agricultural water and 12 percent in natural resource conservation and risk management. The balance of investment financed from public sources is very different between developed and developing countries.

Most public support for agricultural water in OECD countries is for basin level infrastructure[8] – only 13 percent is spent directly on irrigation. The proportions are typically reversed in developing countries with the lion's share going directly to financing of irrigation infrastructure.[9] The difference reflects the fact that in developed countries, the financing of irrigation infrastructure and on-farm investment in OECD countries is largely an area for private investment - the responsibility of the farmers.

This approach is consistent with water sector policies in developed countries that farmers should face the true cost of irrigation service in order to improve allocative efficiency of water resources. By contrast, in developing countries, irrigation financing has been used in pursuit of multiple other objectives such as food security and poverty reduction. In addition, significant public financing in developing countries – particularly China and India - went to 'producer support', largely as subsidies for water or electricity.

In addition, according to the same study, significant public finance went to 'producer support', largely subsidies on water or electricity:

The same study (OECD 2021) shows that significant public support was intended to promote irrigated production through subsidies, particularly in China and India. In 2019, for example, $15.4 billion was spent on agricultural water subsidies worldwide, largely on irrigation-related water or electricity subsidies – with about $12 billion of this spent in India alone.[10] (FAO 2021: 6.2-3]

[7] Across 38 of these countries, total spending on irrigation amounted on average to $195 per hectare, but with wide variations across countries from as little as $4/ha annually (Indonesia) to $460/ha annually (Sri Lanka). More limited information comes from Beyond the Gap, a 2021 World Bank study, which estimated public spending on irrigation for 38 countries which together account for 43% of the global irrigated area. In total, these countries spent an average $4.95 billion each year on irrigation infrastructure and (30 countries only) $867 million annually on O&M. This spending amounts to 0.3% of GDP of the 38 countries and 6.6% of their agricultural value added.

[8] In the FAO/OECD publication referenced, the phrase 'hydrological infrastructure' refers to all expenses to support water use related infrastructure related to agriculture, conservation includes measures towards the conservation of aquatic ecosystems and payment for sustainable water use (payments for ecosystem services), while risk management includes measures to manage water risks (particularly flooding, scarcity or salinity, etc.), and irrigation covers payments to encourage irrigation and development of irrigation on farm.

[9] This pattern suggests that expenditure in developing countries will progressively move toward the OECD pattern of public investment in basin level infrastructure and public goods, and private investment predominating in irrigation] – see Section 5.1 below.

[10] This gives some idea of the extent of distorting subsidies which could be repurposed.

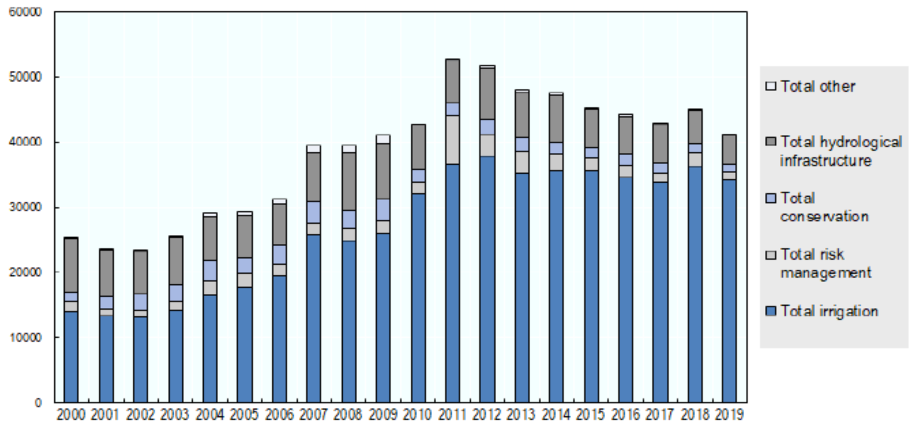


Figure 1: Total water-related agriculture support in 54 countries (2019 USD million)
Source: FAO 2021 based on OECD 2020b

2.1.2Public investment in modernizing large scale irrigation infrastructure

Government remains by far the biggest source of financing for modernization for off-farm infrastructure and large scale schemes.
For more than a century, governments have served as the principal financiers of the large schemes that have been constructed worldwide, including the vast schemes in Asia. In the modern era this pattern has continued, with governments investing in expansion onto the remaining irrigable areas.

As the margins of available land and water have become more limited – and with the huge growth in demand for irrigated products (as discussed in Chapter One) – governments have increasingly invested in modernization in pursuit of more 'product and more $ per drop'. Governments have also sought to reduce the burden on the public purse by requiring farmers to pay a larger share, for example through higher water charges, and by developing various forms of cost sharing, including ways to attract private capital.

Thus, even where government remains the principal (or sole) investor, new cost recovery measures (through collection of irrigation service fees (ISF) or tariffs – increase accountability of I&D schemes' operators and end water users while reducing the fiscal burden.

One such example is observed in Turkey, where the law requires farmers and their water user associations (WUAs) to repay the cost of modernization over the long term (see the box *In Turkey, Government prefinances* and WUAs repay over 25 years).

In Turkey, Government prefinances and WUAs repay over 25 years

The economic analysis of the Turkey Irrigation Modernization Project indicates financial viability at household level, as well as financial viability at the scheme level because of the expected agriculture benefits.

The high upfront costs of the schemes are typical of irrigation projects; however, their benefits are expected to positively transform the local economies and to give a significant boost to household incomes, enabling farmers to repay the cost of modernization over the long-term.

As a result, full cost recovery is required. This is in line with Turkish law which requires WUAs to repay scheme modernization costs over a 25-year period. This requirement has been well-observed in successful irrigation schemes, where the WUAs have a strong record of repayments.

Source: Turkey Irrigation Modernization Project, PAD, December 21, 2018

2.1.3 Public private partnership in irrigation modernization

Over the last few years, the number of initiatives of public–private partnerships in irrigation has increased significantly.
PPPs have been developed to accelerate irrigation expansion, improve operation & maintenance services, and eliminate or reduce O&M subsidies. The most commonly used contractual forms of PPP in the irrigation sector are the management, operation and maintenance (MOM) contract and the infrastructure concession.

Under a management, operation, and maintenance (MOM) contract, the private operator is engaged to provide services in return for a fee.

The box Outsourcing O&M to irrigation service providers (ISPs) in a modernization project shows how shows how these contracts are being structured in the West Bengal Major Irrigation Project to share risks but also to provide performance incentives.

Box: Outsourcing O&M to irrigation service providers (ISPs) in a modernization project

The West Bengal Major Irrigation Project is investing in the modernization of the 400,000 hectare Damodar Irrigation System. A key innovation that the project introduces to improve the quality of irrigation service delivery is the outsourcing of performance-based operation and maintenance (O&M) of canals to private Irrigation Service Providers (ISPs). The ISPs also promote the installation of pressurized micro-irrigation systems. Capacity building and technical assistance is being given to the service providers.

The ISPs will be incentivized to use irrigation water more efficiently and provide canal water to those parts of the Project area that currently overuse groundwater, making the system more sustainable and thus more resilient to climate change.

ISPs will be recruited and paid by the Government of West Bengal and will not seek irrigation fees from farmers. By recruiting ISPs, the Project will improve irrigation services as a first step to incentivize the willingness to pay and to charge for irrigation services, and help make sure that the real costs of irrigation O&M are paid.

The project aims to improve the quality of service delivery through introduction of performance-based operation of selected irrigation canals. Performance will be tracked through a benchmarking system of irrigation performance and client feedback tools (such as user surveys, third party complaint system and citizen report cards).

ISPs are incentivized through performance-linked payments in their contracts. Key performance indicators include the level of compliance with the water delivery schedules in terms of adequacy, reliability and equity. ISPs are paid per hectare irrigated, with incentives to encourage use of water as efficiently as possible while meeting minimum irrigation service quality standards.

Measures to increase efficiency include: reducing non-beneficial ET (for example by enforcing water allocation rules), reducing operational losses, laser levelling of land, installing micro-irrigation technologies, and switching to crops that use less water.

ISPs will also provide services to micro irrigation suppliers and farmers to prepare proposals for obtaining subsidy from the GOI's Pradhan Mantri Krishi Sinchai Yojana (PMKSY) scheme. The number of irrigation suppliers that obtain a subsidy from the PMKSY scheme for the installation of micro-irrigation is linked to payment to ISPs.

The design is based on a successful pilot during the 2017/18 Rabi season. Over 400 firms have been identified that may qualify. Those retained are trained in all potential ways in which efficiency and service delivery can be improved.

As with all such initiatives, there are risks. In this case the experience of working through ISPs was limited to a single pilot in the 2017/18 Rabi season.

Source: Project Appraisal Document: India West Bengal Major Irrigation And Flood Management Project (November, 2019)

Under an infrastructure concession, a private operator is engaged to raise commercial finance for infrastructure development and then construct, operate, manage and maintain the infrastructure.
Investment and financing costs must be recovered through fees. End user risk is significant in irrigation projects where often the users are not fully defined at the beginning of the project. In an innovative form of concession – see the box *In Peru, a concession irrigates 78,000 has* – the finance was actually provided by government from sales of the land to be developed. In this case, the users were clearly defined and committed because they had purchased the land that was to be irrigated.

In Peru, a concession irrigates 78,000 has and also produces power and drinking water

The Peru Chavimochic Irrigation Project is a 25-year co-financed concession to develop the Santa River to improve irrigation on 78,310 ha. The water resources will also be used to feed run-of-river power plants and potable water treatment facilities.

The concession is a Build-Own-Operate-Transfer PPP where the government auctions the land to be irrigated and the proceeds of the sale finance the construction of the irrigation infrastructure by the private partner who then manages and charges for irrigation services.

Source: Public-Private Partnership Legal Resource Center

As experience with irrigation PPP is gained, new formulations and different incentives and risk-sharing mechanisms are being devised

An innovative PPP contract for drip irrigation on 24,000 has in India provided results-based incentives for the turnkey contractor who developed and managed the scheme – see the box India: Innovations in PPP. The contractor also aggregated the farmers in cooperatives and forged links with buyers of the produce. In this case, the success of the farming operation attracted additional private investment. Based on the good results of this first PPP initiative, a further 102,000 ha are now being commissioned using the same PPP model, for an investment of $324 million.

India: Innovations in PPP

Ramthal Drip Irrigation Project in Karnataka was commissioned in July 2017 to cover 15,000 farmers across 24,000 has. The project was implemented through a PPP contract for a seven year period with implementation and commissioning in the first two years and project operation and maintenance and farmer training and marketing support for subsequent five years after project commissioning.

The specific innovation is a performance incentive-driven payment structure with payment of 70% of the capital costs by the end of construction of the system, and the balance of 30% released at 6% per annum for five years during the operation and maintenance phase. Annual O&M payments to the engineering companies are subject to achieving targets for the planted area.

The model has proved moderately successful. The farming operations attracted additional private financing, with a private investment of $3.4 million in nurseries, cold storage infrastructure, and processing units in the area,

Other projects modelled on this one are at their final stages of commissioning, including 10,250 has at Poorigali (Mandya District) with a project cost of $ 80.41 million, 71,040 has at Singatalur (Gadag) with a project cost of $ 141.83 million, and 20,250 has at Tarikere (Chikkamagaluru) with a project cost of $ 102.5 million.

Source: World Bank 2022b: 34

PPP can also be used to invest in basin level infrastructure

A PPP model has been in use in Chile over the last decade to finance the construction of dams for irrigation. Government has provided part of the financing, private partners mobilized the balance and then constructed and operated the dam, and irrigators pay a water fee for the water stored.

Cost-sharing for major irrigation investments in Chile

The Chilean government set up a public private partnership (PPP) arrangement to mobilize private investment for dam construction.

Between 2014 and 2018, the government launched the construction of five large dams, allowing for irrigation of around 8 000 farms covering 40 000 ha in the central and northern regions, for a total investment of $1.3 billion. Three of the five dams were developed under a cost-sharing mechanism: the government financed a part of the total cost, private investors built and manage the dam, and the end users pay the license holder for water stored.

Initially, the approach faced opposition from farmers fearing higher costs of water. Eventually, the project led farmers to shift their production to high-value agriculture (e.g., fruit trees) or to sell their land to other farmers.

Source: Laubenstein 2021, based on Gruère, Ashley, and Cadilhon, 2018.

Overall, experience with PPP has been mixed, with a number of successes – and also failures.

Too often ambitious claims have been made for PPP – and the last decade has shown that a number of striking initiatives have in fact proved unsuccessful. One example is the OMM contract in Ethiopia for operations and maintenance (O&M) services for the Megech-Seraba irrigation project. The $8 million eight-year management contract was to provide irrigation services to 6,000 smallholders over a 4,040 hectare irrigated area. The contract was let with innovative clauses to remunerate the operator based on key performance indicators but without placing demand risk on the operator. This innovative approach was designed to adapt the level of risk transfer to the capacity of the market while providing sufficient incentives for the operator to perform efficiently. However, the arrangements proved unworkable and the contract was cancelled.

A 2014 analysis, which remains valid, concluded that PPP in irrigation is not a new 'panacea' but rather as an additional tool to be used cautiously and only when specific conditions are met.

The box below *When to choose PPP – and what is the appropriate form of PPP* summarizes these conditions. The main lessons learned to date are:

- The need for a favourable environment to promote and develop a PPP, considering the potentially conflicting objectives of farmers, public and private sectors.
- The PPP model with financial contribution of a private party to the capital investment is more appropriate for new and modern irrigation schemes with solid irrigation services demand from commercial farmers
- Other designs of private sector involvement, like management contracts, should be considered when conditions are different (smallholders with subsistence agriculture, etc.);

- It is essential to design the transaction carefully to balance risks between the parties, particularly to reduce demand and payment risk

When to choose PPP – and what is the appropriate form of PPP

- PPP (co-financed between public and private parties) or concession (fully financed by private party) models are more appropriate for new development than for irrigation schemes under operation.
- The PPP or concession models are more appropriate with modern schemes, which require huge investments and private sector know-how.
- There are very few potential private companies for PPP in the irrigation subsector worldwide. The development of any PPP initiative in irrigation must include a sound and efficient marketing campaign.
- The PPP or concession models are not the only mechanisms to involve the private sector in irrigation. There is a wide variety of PPP designs to tailor PPP transact
- Irrigation is a more sensitive subsector for PPP than others such as power generation and distribution, transport, and water supply and sanitation. It is recommended to develop PPP in the irrigation sector only in countries with previous (and successful) experience with PPP in other sectors (and with a solid legal PPP framework). P
- The first project developed under PPP in a specific country will be a showcase of success or failure. Selection of this first project must be made very carefully, ensuring that the most favourable conditions are met. The first
- Experience has taught some good practices of how to reduce demand and payment risks, and also how to improve the attractiveness of PPP projects for final users (farmers).
- It is advisable for the public promoter of PPP projects to hire advisory services with legal and technical skills and international PPP experience to optimize design and avoid unbalanced allocation of risks in PPP design. The private companies
- PPP in irrigation development and management is not a new 'panacea' to solve all the problems associated with bad management of existing irrigation schemes and/or lack of resources for new development.

Source: Review of international experience with public–private partnership in the irrigation subsector. Remi Trier in IRRIGATION AND DRAINAGE (2014) Published online in Wiley Online Library (wileyonlinelibrary.com) DOI: 10.1002/ird.1837

2.1.4 Public support to smallholder irrigation on large scale schemes

Public irrigation projects in many countries have supported modernization for smallholders on large scale public schemes.

Many modernization projects on large scale schemes have included support to on-farm modernization by smallholders. One recent example from Morocco – see the box below - shows both the risks of subsidizing irrigation modernization and the benefits of a flexible approach and course correction in the light of experience

In Morocco, public support enables smallholders to adopt modernization techniques (but this does not necessarily produce water savings)

Morocco has undertaken an ambitious modernization program both for larger farmers and for smallholders - the National Program for Water Savings in Irrigation (PNEEI - *Programme National d'Economie d'Eau en Irrigation*). The program had two main objectives: to improve water delivery service, and to increase water productivity with the expectation that this would 'save' water. It is a good example of government financing modernization at both scheme and farm level, with special attention to smaller farmers and their groups. It is also a good example of the process approach to modernization, and of making mistakes and adjusting.

In its initial years, the program focused primarily on pressurization of water delivery networks and the subsidized promotion of micro-irrigation technologies. After the program had been under implementation for twelve years (2008-2020), government and the World Bank carried out a major assessment. The main findings were that the uptake of modern on-farm technology (mainly drip irrigation) was a success with, on average, a doubling of on-farm water productivity, but that this did not lead systematically to a reduction in the consumption of irrigation water at farm level. In fact, many farmers equipped with drip irrigation used *more* water in order to grow higher value crops, thus contributing to further overexploitation of aquifers.

The assessment concluded that technology aimed primarily at water use efficiency will not save water unless accompanied by water conservation policies. A course correction was required. The subsidized support to micro-irrigation continued but was matched with strengthened regulation and collective aquifer management, including a system of annually determined transferable water quotas.

Source: World Bank 2022a (&M Handbook), based on a note by Remi Trier, Safaa Bahije and Pieter Waalewijn

2.1.5 Public support for small scale collective and individual irrigation

Public investment in several countries has also specifically supported the modernization of small scale collective and individual irrigation.
Many countries have directly supported communal small scale schemes. Examples include Madagascar Petits Périmetres Irrigués (PPI) the Yemen Groundwater and Soil Conservation Project (GSCP), and the Morocco Petits et Moyens Hydrauliques program under the Community-Based Irrigation Project.

A notable example of public support to very small scale individual and communal irrigation was the Niger Private Irrigation Promotion Project – see the box below. The project successfully used matching grants to support the modernization of thousands of smallholder irrigation operations and also built sustainable institutions for further development and financing of irrigation modernization.

Public support to smallholder irrigation modernization under the Niger Private Irrigation Promotion Project brought significant benefits to poor households and built a sustainable institutional framework for further modernization

The project used participatory approaches to develop, test and disseminate simple, low-cost irrigation and production technologies for private farmers. It built up a private, federating body, the *Nigerien Association for the Promotion of Private Irrigation* (ANPIP).

The bulk of the project – the Irrigation Investment Component - helped members of project-supported producer organizations to invest in irrigation modernization through a matching grant facility and through support to Micro-Finance Institutions (MFIs).

The outcomes were highly successful, with 16,500 ha of new or modernized irrigated area and considerable increases in productivity and output. Nearly half (47 percent) of the total beneficiaries were women and young adults. Farmer revenues rose to 1.5 to 3 times the average income in Niger.

Other impacts included better access to land, increased savings, increased agricultural investment, a growth in employment in both on- and off-farm activities, better access to schooling, and enhanced food security and nutrition at the household level. At the national level, it was estimated that incremental production resulting from the project met the demand of nearly 200,000 people and made a significant contribution to closing Niger's chronic food deficit.

Source: Niger Private Irrigation Promotion Project (PIP2) ICRR, June 23, 2009.

2.2 Development assistance for agricultural water and irrigation

2.2.1 Global levels of development financing of irrigation modernization

Development assistance for irrigation is relatively small compared to total government financing

In the age of rapid irrigation expansion in 1960s and 1970s, Official Development Assistance (ODA) for irrigation was relatively high. However, multilateral lending declined rapidly post 1985 – and the character of the projects changed, with less financing for expansion, and more for modernization.

Recent ODA financing for irrigation in developing countries has been around $1.4 billion a year[11] - almost all in Asia and Africa (see *Table 2: Official development assistance: agricultural water resources*). Thus, ODA for irrigation is relatively small in relation to government financing ($1 billion vs. $40 billion annually); and also small in relation to total ODA for agriculture (around $7 billion annually) and to total ODA ($166-195 billion annually). [FAO 2021: 5.2; OECD 2020a: 1-2]

Table 2: Official development assistance for irrigation (current USD)

	2014	2015	2016	2017	2018
Total ODA	**1 097**	**1 099**	**970**	**1 061**	**1 084**
From DAC countries	434	435	376	322	349

[11] Including $400 million in non-concessional finance.

From Non-DAC countries	52	96	30	72	136
From Multilateral agencies	611	568	564	667	599
Other official flows	**406**	**303**	**408**	**452**	**368**

Note: DAC countries are countries members of the OECD Development Assistance Committee (for the list see http://www.oecd.org/dac/development-assistance-committee/).

Source: OECD (2020a).

2.2.2 International Financing Institutions (IFIs) are actively investing in I&D modernization

IFI projects are a rich source of knowledge and innovation on modernization.

Although IFI financing forms a relatively small part of global investment in irrigation modernization, it is a first rate source of knowledge due to the clear documentation on most IFI-supported projects. IFI-financed projects are also a nursery for innovation, with many governments relying on IFIs as much for support to innovation as for investment capital.

Modernization has become an increasingly common consideration in IFI-financed projects

Amongst IFIs, the World Bank has always been a significant financier of irrigation, providing more than US$ 38 billion since the 1950s, and more than US$ 8 billion in the last decade alone. In recent years, much of this support has been to modernization, both on-farm and off farm, accompanied by support to management systems, to upgrading of agency staff, and to farmer knowledge and skills.

A 2020 review of closed and active World Bank-financed irrigation projects found that 113 irrigation projects (36 active, 77 closed) included the term ‘modernization’ in their title or their objectives. A ‘modernization’ objective has become increasingly common – with 81 of the 113 projects mentioning modernization having been approved in the last two decades (2000-2020).

The focus of this modernization investment has shifted in recent years.

An early focus on canal lining has reduced, with more recent projects including pressurized conveyance, on-farm pressurized water application, and automatic control (see the box Modernization in recent projects). Modernization of traditional schemes has also become an important business line (see the box Modernization of traditional schemes).

Box: Modernization in recent projects

In the Morocco project Modernization of Irrigated Agriculture in the Oum Errubia, the elevated canals were replaced by pressurized pipes and on-farm systems were adapted for drip irrigation. The same principle was applied in projects in other countries, including Tunisia, Cyprus, Turkey and Bosnia.

Over the last three decades, operation of canal systems was improved through the installation of long crested weirs in a number of projects, including the India National Water Management Project, which included Tamil Nadu, Andhra Pradesh and Karnataka; the Vietnam Water Resources Assistance Project; and the Albania Water Resources and irrigation Project.

Other projects included the construction of storage reservoirs, for example, the construction of a reservoir alongside the Iber-Lepenc canal in Kosovo, and the Chotiari reservoir in Pakistan.

Modernized control systems have been introduced in a number of projects. Supervisory Control and Data Acquisition (SCADA) systems have been successfully implemented in the Dau Tieng schemes under the Vietnam Water Resources Assistance Project and in Kososvo along the Iber-Lepenc Canal. Centralized control has been installed along main canals in Morocco. Remote monitoring is being supported under the recently approved West Bengal project.

The experience has not always had positive outcomes. For example, dynamic regulation of the Majalgaon canal in Madhya Pradesh State, India stopped operating after a few months because of lack of an integrator contractor (low voltages in power lines, frequent interruption of radio-communications).

Source: Review of Closed and Active Projects with Modernization Components (Plusquellec, 2020)

Box: Modernization of traditional schemes

Afghanistan: Khanabad: Like other systems in Afghanistan the Khanabad scheme consisted of loose-stone bunds at several locations in the river bed to divert water from the river into ungated canals with brushwood drops and check structures controlling the flow through the canals to primitive farm turnouts. Modernization consisted in replacing 11 diversions made of local materials with only one weir and a main canal supplying a series of secondary canals.

Nepal : A similar design principle was adopted for the modernization of the Rani Jamara Kulariya scheme. Flow dividers, a structure well known in other valleys in Nepal, were introduced in the design.

Yemen: Traditional spate irrigation works in Yemen aimed at diverting flash floods with annually rebuilt earthen bunds. The challenge is **to** harness the flood waters, which may occur in one or two short-lived spates each year, and to divert the water into canals. Modernization comprised concrete weirs and diversion structures constructed in the 1970s in the Tehama and in a spate improvement project in the 2000s which also strengthened governance systems.

Source: Review of Closed and Active Projects with Modernization Components (Plusquellec, 2020).

2.2.3 Trends in modernization for future IFI investments

Existing modernization technology can provide responses in projects to the emerging needs of irrigators.

A recent (unpublished) report *Sustainable Irrigation Performance under Changing Conditions* (World Bank 2018a) highlighted the main areas where modernization is likely to be important in the coming years – and hence the technologies that are likely to be appropriate in future modernization projects. At system level these areas include new technology in system infrastructure and management; more complementary surface and groundwater combinations; improved conveyance efficiency; improved main system management to provide arranged or on-demand service; and technology innovations such as SCADA systems, decision support and asset management software including AI, and soil water budget models. The innovation in the Indonesia SIMURP project is the introduction of irrigation service agreements monitored by remote sensing to make irrigation service delivery more accountable.[12]

At farmer and on-farm level, the study also predicted growing demand for more controlled water application, including pressurized water application technology and construction of on-farm storage. In addition, digital solutions and application of wireless technology are also likely be key - including apps for ET estimation, irrigation scheduling, water ordering, staff gauge reading, discharge measurement, performance assessment and performance-based management and market price information.[13]

2.3 Finance for farm-level irrigation and modernization

2.3.1 Significant demand for on-farm modernization – but limited access to finance

Historically, finance for irrigation at farmer level been small scale and largely informal

Farmers across the world have developed all sorts of agricultural water management infrastructure ranging from simple run-off/run-on improvements of slopes (e.g., Yemen) and the construction of terraces (e.g., Nepal) to elaborate surface water diversion, and long range groundwater transfer (*qanats* of Iran and Arabia). These investments were largely financed by community subscription and family resources, and by sweat equity.

In recent years, new technology and new markets have stimulated farmer interest in modernization and much of the 'modern' technology, particularly on-farm, is relatively affordable.

For example, the explosive spread of groundwater development has been largely financed by farmers themselves. A huge range of new technologies and equipment have become available to improve water efficiency and productivity, notably pressurized technologies like drip and sprinkler, and associated production methods, like the use of greenhouses.

[12] On SIMURP: The World Bank is providing support to the Government of Indonesia (GOI) to improve irrigation services and strengthen the accountability of the management of irrigation schemes. One of the innovations that the project is piloting is the preparation and signing of Irrigation Service Agreements that describe the procedures, rights, and obligations of service providers and beneficiaries regarding irrigation water entitlements, allocations, ordering processes, deliveries and procedures in case of water shortages, as well as for maintenance and canal closures for maintenance. The project intends to pilot the use of remote sensing to monitor the implementation of the contracts.

[13] On this, see Section 4.4 below.

New markets for cash crops have made these investments widely profitable. Much of this technology is for improvement of on-farm water efficiency and does not require extensive built infrastructure. It is therefore in principle more easily affordable - see the box *Low-cost modernization for poor smallholders.*

However, self-financing still predominates, and even low cost on-farm modernization is out of the reach of many farmers.

Evidence from India shows that 80% of financing for smallholder irrigation modernization stems from farmers' own savings, or from their families and local support. This has greatly limited the scale of investment. [de Jong; and FAO 2021: 54]

Public sources of finance for farmer modernization have been limited and are often skewed towards the already better off

Although some new financing providers and products are emerging (see Chapter Four below), there is huge pent up demand from farmers. Finance from existing sources is skewed towards larger, already better off farmers. The vast majority of farmers in SSA, for example, are resource-poor and do not easily qualify for financing. This particularly applies to the poorest and most disenfranchised segments of society (including women). [World Bank 2021b]

Financing responses such as access to credit and subsidies can provide a critical bridge across the affordability gap.

One powerful mechanism is communal ownership and service provision. The box *Pooling access to solar pumps allows very poor farmers to irrigate* shows how an asset that is out of the reach of individual farmers is affordable when it provides services to a farmer group.[14] [World Bank 2021b]

In Punjab, matching grants were used to develop private sector provision of laser land levelling services – see the box Matching grants help develop sustainable private laser land levelling services in Punjab. These services are now not only affordable but are profitable enough to be sustainable within the private sector.

Box: Low-cost modernization for poor smallholders

Examples include:

- petrol and solar pumps with plastic pipelines
- storage tanks
- on-farm irrigation technologies (hoses, sprinklers, and drip systems).
- simple diversion weirs and canals on gravity schemes, usually involving groups of farmers.

Costs may be very low and high labor requirement can offset the equipment cost.

Costs per hectare range widely depending on the country, system type, and quality. In rudimentary systems such as hand-dug wells with bucket-and-ropes, or pedal pumps to abstract shallow groundwater, or simple gravity earth canal schemes, high labor requirement can offset the equipment cost.

And equipment does not have to be costly. While high-quality, fully equipped pumping installations will cost many thousands of dollars per hectare, cheap, low-quality petrol pumps can be bought for a few hundred dollars.

Sources: World Bank 2021b; and FAO 2021

Pooling access to solar pumps allows very poor farmers to irrigate

The Jharkhand Opportunities for Harnessing Rural Growth (JOHAR) project deployed a cycle-mounted solar pump. This is a small moveable device that farmers can move from field to field to irrigate up to 0.5 acres with a discharge of 3–4 liters per second (lps).

Two solar panels with 320 W capacity each are installed to operate a 0.5 HP pump-set. The total cost of this cycle mounted solar pump is around US$ 650. The units are assembled locally after solar panels have been procured with project financing.

Farmers use the units on a rotational basis and over 100 have been deployed. JOHAR targets to scale this model to an additional 2,000 units and farmer groups.

The project trains locals from within the village to operate the unit, to do basic O&M for solar panels, and to operate pumps. Full cost recovery is practiced in order to make the system sustainable.

Source: World Bank 2022b: 29

[14] The reason why pumps are so popular is that ownership is private, individual and one no longer has to rely on one's neighbor. Making pump ownership communal may make a pump lose its main attraction.. An alternative model is private pump ownership and sale of water to neighbors. This may, however, reduce access by the poorest.

Matching grants help develop sustainable private laser land levelling services in Punjab

Laser land leveling was initiated in the Punjab province of Pakistan in 1984. After some initial trial and error, techniques were improved and by 2006 some 285,000 hectares had been improved. Other provinces followed suit, setting up publicly-run services.

In 2006, the Punjab government decide to speed up implementation by involving private sector service providers. Matching grants of 50 percent were made to enable the private sector to acquire the necessary equipment. As a result, annual laser land leveling capacity in the province increased from 14,000 hectares a year to 300,000 ha. By 2016 the private sector services were effective enough for the government to end public provision and to transfer its remaining units to the private sector. Today there are over 16,000 laser land leveling units providing services to the farmers across the province.

The overwhelming success of the technology and delivery method was replicated in other provinces, and the model has spread to neighboring India and Afghanistan.

The lessons from this experience are:

- Start modest, learn from mistakes, and adopt a step-by-step progressive approach.
- Smart subsidies can create a dynamic of modernization, in this case unleashing the energy of the private sector.
- The lessons of success can be disseminated and trigger modernization on a broader scale, in other provinces, in neighboring countries, and beyond.

Source: World Bank 2022a Country Case Study: Laser Land Levelling in Pakistan

2.3.2 Recent years have seen the emergence of new private and not-for-profit providers of finance for smallholder modernization

A number of private and not-for-profit agencies lend to smallholder irrigators.

Most of this financing is not specifically directed to irrigation or its modernization but to agricultural development more generally, However, irrigation investment forms an important part of the demand. One example is the thrift CARD SME Bank in the Philippines which successfully partnered with the International Finance Corporation (IFC) to expand access to finance for small-scale farmers, with terms up to three years which matched the pay-back period of simple irrigation investments (see the box A thrift bank *in the Philippines successfully builds a loan* program for smallholders on blended finance).

There are numerous rural banks, SACCOs and micro-finance providers that provide financing.

Examples are the *Grameen Bank* in Bangladesh and the network of *Banques Populaires* in Rwanda. There are, however, limitations imposed by the typically small and short term nature of the loans offered which are not well adapted to the relatively high costs and longer payback period of irrigation investment

A thrift bank in the Philippines successfully builds a loan program for smallholders on blended finance

In the Philippines, bank loans are out of reach for many smallholders because they cannot comply with the documentary procedures and collaterals required by the banks. Due to high exposure to extreme weather events and perceived low creditworthiness of borrowers, investors consider agricultural lending very risky.

The thrift CARD SME Bank in the Philippines partnered with the International Finance Corporation (IFC) to expand access to finance for small-scale farmers. During a pilot phase starting in 2013, CARD SME Bank in cooperation with IFC, designed and rolled out an agri-finance strategy, trained loan officers on credit assessment in the sector and developed a credit scoring tool to assess viability of each crop and to understand production cycles. Linking the repayment schedule to the production cycle minimized repayment risks, and overall loan disbursement and the number of client farmers grew substantially.

After the successful pilot phase, IFC provided a seven-year concessional loan package at competitive market rates to CARD SME Bank in 2016. The proceeds of the loan were blended with CARD SME Bank funds and disbursed to client farmers, tailored to their needs. Loans would range from three months to three years with volumes between about 500 and 85,000 EUR.

Financing is accompanied by advisory services enhancing farmers' awareness of new technology, innovations and production and marketing strategies.

With this approach, CARD SME Bank's loan disbursement rose by 241% between 2016 and 2017 to reach underserved small-scale farmers and agribusinesses. With this new access to finance, farmers were able to expand production, input supply, and transportation and to improve their income.

Source: Laubenstein, 2021.

2.4 Farmer-led Irrigation Development (FLID): financing small scale and individual private irrigation[15]

In recent years, there has been a revival of focus on 'farmer-led irrigation development' (FLID)

As discussed above, farmers have taken the initiative to develop irrigation since time immemorial. After a century in which government-led irrigation has been dominant, there has been renewed interest from governments and the development community in the potential of farmer-led irrigation development (FLID). From the farmers' viewpoint, farmers worldwide – but particularly in SSA – are faced with growing climate insecurity, low water productivity and poor livelihoods. In consequence, farmers have increasingly been developing and using all and any available water resources to sustain and improve their production. From the viewpoint of governments and development agencies, support to FLID offers a way of helping very poor smallholders to improve their incomes whilst building resilience to climate change.

A number of countries and programs have supported this renaissance of FLID

Support programs have tried to help farmers overcome the typical significant constraints and barriers to entry. These constraints include lack of knowledge, poor local availability of equipment and support, lack of access to output markets and value chains, and little or no access to the means of financing irrigation development. Support programs have used market-based and public-private partnership approaches to overcome these constraints – a good example is that of Rwanda, where second generation problems are now being tackled (see the box *Rwanda's successful FLID financing program*). Another long-running program which targets smallholders in Latin America is Chile's cost-sharing grant program for small-scale initiatives – see the box *Public-private cooperation for FLID in Chile*.

Box: Rwanda's successful FLID financing program – and how to make it more inclusive and efficient

The Rwanda government launched the Small-Scale Irrigation Technology (SSIT) Program in 2015 to catalyze the development of 25,000 ha of newly irrigated land over 10 years (2015-2024). The SSIT Program is designed to help farmers to overcome the financial and knowledge constraints to converting to high value irrigated agriculture.

The farmer applies to the program via the local government. Government provides a partial subsidy of 50 to 75% of the equipment cost with a ceiling of $1,500 per ha. The farmers make the balance of payment (25% to 50%). If needed, farmers are helped to obtain loans from MFIs or SACCOs to mobilize the money for their portion.

The profitability of business proposals is a key determinant for farmers' eligibility. Once eligibility is confirmed, the farmer can reach out to any of the Government's prequalified irrigation equipment suppliers to select the preferred irrigation kit. The farmer pays his/her portion directly to the supplier, the supplier receives the remaining portion from the Government, at which point the supplier proceeds with installation. The farmers receives extension advice on use of the irrigation equipment and on irrigated farming

The Program is progressing according to schedule. In its first seven years of implementation, it catalyzed action by 4,100 farmers who developed irrigation of more than 17,000 ha by 2021. This corresponded to an annual Government

[15] This section draws extensively on World Bank 2021b.

investment of 1 million USD, matched by another annual 1 million USD of farmers money.

In 2022, the government joined with IFC, WRG2030 and farmers to reflect on how the SSIT Program could be enhanced. Key recommendations were to:

- make the scheme more inclusive by opening it to land renters, notably the landless and youth and women who were previously excluded by the land tenure requirements
- develop the private financing market by working with financial institutions to raise awareness and knowledge about irrigation and FLID and to develop fit-for-purpose financial products that could increase farmers' capacity to raise the co-payment and – over time – reduce Government's payment share.
- make the process faster and more transparent with a digital application process that would reduce turnaround time for farmers, and also allow for better record keeping and process monitoring.

Source: World Bank 2022c and a note by Innocent Nzeyimana (inzeyimana@ifc.org).

Public-private cooperation for FLID: Chile's cost-sharing grant program for small-scale initiatives

An initiative to support private investment in irrigation in Chile is the cost-share grant program for small-scale initiatives. Under this program, small and medium sized owners can complement their investments in irrigation and drainage projects for community or individual works with public grants. Since the program started in 1986, about 23 000 farmers have benefitted including a growing number of small farmers over time. In total, this has contributed to irrigation development on 200 000 ha, The program also enabled 500 000 beneficiaries to shift to pressurized irrigation, representing a total area of 325 000 ha.

Source: Laubenstein 2021, based on Gruère, Ashley and Cadilhon, 2018

Since 2018, the World Bank and partners have developed a special program to support FLID.

In 2021, the WB published a comprehensive FLID handbook showing how governments and development agencies of all types could support FLID, building the enabling environment - the policies, incentives and regulations in order to help the sector thrive and manage its potential negative impacts and facilitate and empower a wider group of farmers.

By 2022, the World Bank Group had supported client governments in catalyzing FLID across 13 countries.

More than 430 million USD had been earmarked for FLID interventions, leveraging at a minimum 65 million USD of farmers' money, In addition, wider policy support was catalyzing private sector support and financing. Overall, support to FLID to 2022 is expected to have translated into 185,000 farmers accessing irrigation over 85,000 ha. [World Bank 2022c]

FLID goes well beyond sources and practices traditionally thought of as 'irrigation'.

In fact, 'agricultural water management' is the more appropriate concept, including development of valley bottoms, hill slopes, flood recession, city drains etc. The FLID concept embraces a myriad technical forms from the simplest run off/run on systems to pedal pumps or reuse of treated wastewater.

FLID has aroused strong interest across many countries with early results underlining the need to ensure equity and inclusion

Because access to water resources is typically skewed towards the better off – in fact, that better access is a primary reason why the better off are better off – FLID programs have to emphasize equity and to focus not only on 'irrigation development' but on improving water management and farming for the poorest more generally. Early results from Ethiopia demonstrate the need for this – see the box Care is needed to ensure that FLID financing does not benefit only the better off.

FLID also runs the risks of a weak governance framework and poor regulation of water resources management and sustainability

In Kenya, for example, agriculture is dominated by smallholders - three-quarters of crop production takes place on farms of less than 3 ha. These farmers are mostly involved in cash farming in vibrant value-chains linked to local and international markets. Producing high value produce such as fruit and vegetables, many of these smallholders have started to use irrigation in order to have the necessary water control and to build resilience to climatic vagaries. However, access to water resources and actual water use are poorly regulated and this has led to problems of sustainability and conflict among users – the box below highlights the problem and the actions the government is taking to strengthen coordination between national and county government, parallel stewardship, and water governance interventions to ensure sustainable water use.

In Uganda, a concrete safeguard framework has been proposed to align FLID and water resource management and sustainability – see the box Sustainable water resource management in Uganda under FLID.

Box: Care is needed to ensure that FLID financing does not benefit only the better off

A 2021 IWMI study found that public investment in farmer-led irrigation is more likely to benefit cash-crop cultivators and the better off.

The study examined efforts to expand farmer-led irrigation development in Ethiopia, including groundwater irrigation using solar irrigation pumps, as an instrument for poverty reduction and food security. Findings were that land suitable for groundwater-based irrigation is owned by wealthier households and that public investment in farmer-led irrigation development targeted at reducing up-front investment costs and stimulating agri-businesses will likely benefit these wealthier farmers. Less wealthy farmers may not benefit from public investment in FLID.

The study concludes that special consideration is needed on how public investment in farmer-led irrigation expansion can support poorer, rainfed producers, particularly as they may be at higher risk of crop loss due to climate change. FLID approaches should consider both spatial land suitability for irrigation and farmers' socio-economic characteristics. Public and private actors supporting FLID need to provide equitable access to improvements in agricultural water management for poorer farmers and tailor financing to their needs. These interventions should go hand in hand with strengthening irrigation supply chains, irrigation services, and agricultural markets.

Adapted from a 2021 paper by Kashi Kafle, Impact Evaluation, IWMI

See: https://www.iwmi.cgiar.org/2021/07/study-finds-public-investment-in-farmer-led-irrigation-is-more-likely-to-benefit-cash-crop-cultivators-and-the-wealthy/

Kenya: Strengthening governance and sustainable resource use while promoting FLID

Farmers across Kenya are developing their own irrigation systems individually or in small groups. There are, however, challenges of sustainability and governance which are emerging. Government wishes to support much more rapid expansion of FLID but needs to address these emerging problems.

The Government of Kenya requested the World Bank and 2030WRG to support an assessment to identify the constraints to rapid small-scale irrigation development. A framework of action was developed to strengthen governance and sustainable resource use while promoting FLID:

- Strengthen the water permit system for regulating water rights and use and set up County Irrigation Development Units (CIDUs) with a digital platform to aggregate the farmer demand for irrigation.
- Promote individual farmers' action in irrigation by organizing farmers in groups to reduce transaction costs for value chain and financing institutions and de-risk private actors lending to farmers.
- Introduce a partial subsidy for irrigation equipment and tax reduction to improve affordability of irrigation equipment.

Source: World Bank 2022c and a note by Joy Busolo (WRG2030) jbusolo@worldbank.org

Box: Sustainable water resource management in Uganda under FLID

In Uganda, the FLID program under the Uganda Intergovernmental Fiscal Transfer has developed procedures for sustainable water resources management. The program:

- collects coordinates of the individual farmers developing irrigation, so as to have the tools to assess potential cumulative impacts as more farmers join the process;
- maps the information and based on those maps, initiates a dialogue with the water basin authorities
- uses an environmental screening tool for each site collecting basic information on the water source, water availability over the year, conflict over water, downstream users, etc with the local government environmental specialists randomly selecting a certain percentage to double check the information.

Source: based on a note by Gabriella Izzi and Ruyi Li

Chapter Three – New ways to finance I&D modernization

3.1 New financing instruments

3.1.1 Blended finance to leverage private capital for modernization

Blended finance can play a major role to scale up commercial investment

Blended finance essentially uses development finance (such as ODA and funds provided by philanthropic foundations) to leverage additional finance. Blended finance models can give incentives to financial institutions to provide affordable loans where the market would not. [FAO, 2020]

Blended finance brings three significant benefits to correct 'market failure'. First and foremost, it mobilizes extra financing. Second, it can significantly improve the risk-return profile of water-related investments for commercial financiers by underwriting part or all of the risks. Third, It can serve a market building role, to help strengthen the financing systems upon which investments rely.

Although blended finance facilities for infrastructure finance have multiplied in recent years, they have had limited impact in irrigation.

In the water sector (see the box *Blended finance is only slowly extending to agriculture and irrigation*) blended finance has largely financed water and sanitation projects, which are more 'bankable''. However, the number of blended finance vehicles targeting the agricultural sector in developing countries has been rising over the last decades and according to one report (Convergence 2019], the sector is "ripe for more blending". In irrigation, transactions have mostly focused on Sub-Saharan Africa with relatively small deal sizes (ca. $55 million) and primarily in the form of concessional debt or equity accompanied by technical assistance. Nonetheless, there are good prospects that blended finance can be applied both to large scale irrigation infrastructure and to small scale and individual lending for irrigation [Laubenstein, 2021].

Box: Blended finance is only slowly extending to agriculture and irrigation

Over the last two decades, there has been a growing interest in the use of blended finance as reflected by the increasing number of blended finance facilities. Between 2000 and 2016, a total of 167 facilities which engage in blending were launched, with a combined sized of $31 billion (in terms of commitments).

In the water sector to date, blended finance has been largely applied to water and sanitation projects, with estimates that official development finance interventions mobilized an additional $1.5 billion of private resources in 2012-15 for that sector. The main leveraging instruments in the water sector were guarantees ($1 billion), followed by syndicated loans ($388 million).

The agriculture and irrigation sectors attracted only a small share of this blended financing. In 2017-18, only 3.3% of the amounts mobilized from the private sector by official development finance interventions were dedicated to the agriculture sector (compared to 28% to the energy sector).

Source: Financing water Investing in sustainable growth OECD ENVIRONMENT POLICY PAPER NO. 11

One area where blended finance has had some success is in encouraging private providers to enter the market, including for irrigation.

Some of these entrants are classic financiers – banks and NBFIs. One example is Rabobank of the Netherlands which has partnered with UNEP to set up a blended financing structure with a separate de-risking mechanism.

Blended finance and de-risking: the case of AGRIFund3

Rabobank of the Netherlands[16] has joined with UNEP to launch: the AGRIFund3, which is a blended financing structure with a dedicated side entity for de-risking. Rabobank approves a loan to farmers, while the part of the loan that exceeds the risk appetite of the bank is covered by AGRIFund3. The fund finances projects which protect forests, promote sustainable agriculture and improve rural livelihoods, targeting initiatives with long-term viability.

Source: FAO 2021b based on a presentation by Hans Loth, Group Executive VP, Global Head of UN Environment Partnership at Rabobank

3.1.2 Rentals, leasing and pay-per-use as low entry cost models for modernization

Low entry cost models for modernization include rentals, leasing and pay-per-use
Several mechanisms can finance irrigation at relatively affordable costs while avoiding the problems of lack of collateral or other aspects of weak bankability. Rental arrangement, may include, for example, models where sprinkler systems and rain guns can be rented for an irrigation season and returned after the season. Under lease agreements, the owner of the irrigation asset (retailer, landlord, equipment manufacturer, public sector agency etc.) retains ownership but leases long term use to a farmer or farmer collective. With pay-per-use, providers simply provide a service. In India, for example, mobile solar energy providers power a farmer's pumps in return for a volumetric fee for each use – see the box *India: financing irrigation as a service – Pay-as-you-go for mobile solar irrigation*. [World Bank 2022b: 26]

[16] Rabobank is a Dutch cooperative bank with a commitment to 'being a leading bank in the field of food and agriculture worldwide'

India: financing irrigation as a service – Pay per use models for mobile solar irrigation

The objective is to make irrigation services accessible to very small farmers while protecting aquifers and reducing GHG emissions. The solution is to promote piped irrigation with solar power. However, while solar pumping is a cheaper source of energy, it is associated with high up- front costs. The solution is to provide mobile solar irrigation units on a pay-per-use basis.

How it works

- Business-to-Consumer (B2C) companies provide mobile solar irrigation solutions either as a subscription service themselves or sell their mini solar vans to WUAs / farmer collectives to own and operate on a community ownership basis.
- An uber-like satellite platform tracks the distance and route taken by the vehicles
- Real time online data analytics on water abstraction are generated
- A smart card recharge option ensures financial transparency vis a vis quantity of water consumed

Under the subscription service model, a van or small three wheeler vehicle is equipped with solar panels. It is owned and operated by retailers where farmers 'pay-as-you-go' for each irrigation service. A fintech platform helps tracks usage and payments can be made via prepaid cards or via online payment platforms.

Under the community ownership model, joint liability groups (JLGs) or farmer collectives use existing capital or borrow to purchase or lease solar bicycles or small vehicles equipped with solar panels. The JLG or farmer collective sets its pricing and charges farmers based on usage

Source: World Bank 2022b: 29. See also: https://www.youtube.com/watch?v=oJflugfH2c8

3.1.3 Leveraging finance for modernization through value chain partners

Particularly relevant to smallholders are 'value chain partners' where Business-to-Business (B2B) and Business-to-Customer (B2C) arrangements can be financed in several ways.
These partners include last-mile service providers and manufacturers, and retailers of irrigation equipment (e.g., solar pumps, micro-irrigation equipment, etc.).These businesses can sell, lease, or rent irrigation equipment and products, and provide pre-and after sale services. They may also simply provide consumer credit, which is now well established across Asia, particularly in India (see the box *Consumer credit in India*).

Consumer credit for irrigation modernization in India

Consumer credit for irrigation modernization in India to finance investments in micro irrigation is a growing business. Just as in the USA when you buy a car, the supplier is providing the credit. In India, *Jain* and *Netafim* are major providers of this kind of financing. They also apply for and pass on the subsidies, which are provided directly to the suppliers in many states in India.

These suppliers run out of liquidity at some point, but it is fairly easy for them to obtain a bank loan, as they are large firms with a credit rating. Additional soft loans can be provided from public resources.

This form of credit applies on a large scale. Although it may not be so easily accessible by the poorest, it has contributed to a very significant increase in the acreage under micro-irrigation.

Source: Based on a note by Ijsbrand de Jong

Farmers can pay for these purchases and services through pay-as-you-go solutions, rental arrangements, or through outright asset purchases.

It may be that the suppliers have their own sources of finance that they can extend. There are also mechanisms by which either the supplier or the farmer can access credit or public subsidy. In the case of Rwanda's Small-Scale Irrigation Technology (SSIT) Program, for example – see the box: Rwanda's successful FLID financing program in Section 2.4 above – the farmer purchases from a pre-qualified list of suppliers. The supplier receives the subsidized (75%) of the cost from the Government, while the farmer pays 25% of the cost directly to the supplier

Nigeria's ACRESAL program, which supports FLID, uses a results-based financing (RBF) facility to stimulate irrigation supply and service companies, third-party financing, and agribusinesses to serve farmers in remote areas and in the bottom-of-pyramid markets – see the box *Catalyzing private sector innovation through value chain partners in irrigation in Nigeria*. Farmers approach pre-selected irrigation equipment suppliers and purchase suitable technology directly. Partial subsidies are provided directly to the suppliers who record their sales and component details on a 'Financing Facility' platform, and receive payment based on results. Results are verified, including by spot checks on farmers' satisfaction.

Box: Catalyzing private sector innovation through value chain partners in irrigation in Nigeria

Prospects for FLID in Nigeria are based on massive potential and supported by results-based lending.

Nigeria is well-endowed with both groundwater and solar resources and has a well-established network of home-solar technology suppliers, all of which provides potential for development of smallholder solar-powered irrigation. However, finance and technology constraints are holding farmers back. The purchase cost of irrigation equipment is high and although supplier loan financing for solar-home equipment is well-established, irrigation equipment suppliers are unwilling to take the lending risk. Informal micro-financing solutions have prohibitively high interest rates and formal financing requires collateral. Local availability of quality equipment near farmers is generally limited.

How the program works:

Nigeria's ACRESAL program uses a results-based financing (RBF) facility to stimulate irrigation supply and service companies, third-party financing, and agribusinesses to serve farmers in remote areas and in the bottom-of-pyramid markets. The target is to support 20,000 farmers for the development of 10,000 ha of newly irrigated land through FLID 2021-2027.

Farmers approach pre-selected irrigation equipment suppliers and purchase suitable technology directly. Partial subsidies are provided directly to the suppliers who record their sales and component details on the financing facility platform, and receive payment based on results. Results are verified, including spot checks on farmers' satisfaction.

The program began in 2021 with FLID awareness and information for mass-outreach, and the setup of the digital aggregation platform for farmer registration. Awareness-raising covered irrigation benefits and technical and financing options through media, ACRESAL demo-farms and suppliers' own-initiatives.

Source: World Bank 2022c and a note by Emmanuel Chinedu Umolu eumolu@worldbank.org

In Kenya, revenues from out-grower contracts are used to guarantee repayment of irrigation investment loans

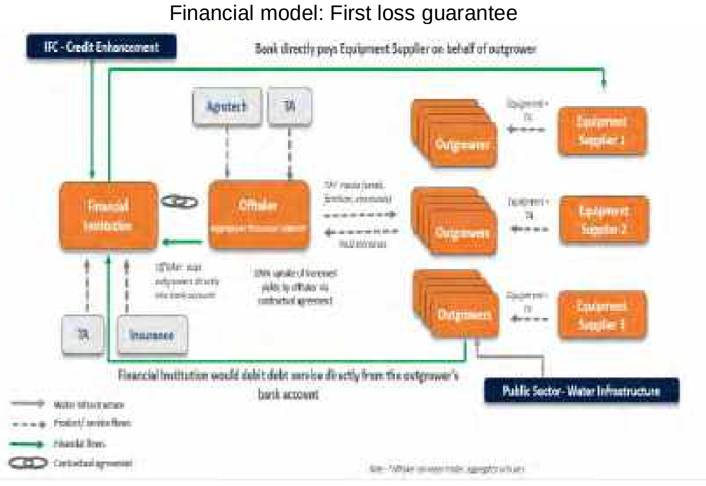
A model developed by 2030 WRG together with IFC convenes stakeholders from across the value chain to catalyze increased investment in efficient irrigation.

- With a first loss guarantee in place, the financial institution lends to the intermediary who has a contract with the farmer to buy his produce. The intermediary could be a local trader, aggregator, or exporter.
- The trader purchases irrigation equipment on behalf of the farmer
- The irrigation equipment supplier then supplies the irrigation technology or equipment plus technical assistance to the farmer.
- The bank pays the equipment supplier directly on behalf of the out-grower
- Finally, the buyer pays back the loan over time to the financial institution by direct deduction from the crop proceeds.

The project aims to increase yields up to seven times through drip and sprinkler irrigation with proportionately increased incomes, while reducing water consumption per hectare by up to 35- 45%.

Source: World Bank 2022b: 27

Financial model: First loss guarantee



The trusted relation between trader and outgrower can be used to underwrite lending for irrigation investment

Under many out-grower arrangements, contractual advances may be made against crop delivery: the purchaser agrees to buy the crop and in exchange provide an advance in cash or kind to enable the farmer to invest in modernization or to produce a crop. In a project in Kenya, this model was extended to allow farmers to buy irrigation equipment from suppliers using bank finance and guaranteed by the subsequent cash flow from sale of produce – see the box *In Kenya, revenues from out-grower contracts are used to guarantee repayment of irrigation investment loans*. The key is the trusted and contractual arrangement between farmers and the purchasers of their produce which provide an assured cash flow for repayment of credit. [World Bank 2022b: 21A, 25]

3.2 Supporting instruments: guarantees and insurance to underwrite lending and risk management for modernization

3.2.1 Guarantees

Guarantees can support the provision of credit either at the level of a major investment or at the level of credit to irrigators.

In the case of a major infrastructure investment, a guarantee could be extended to underwrite the credit quality of the service provider or irrigation agency, enabling commercial banks or bond investors to step in to provide finance, For example, for large irrigation infrastructure projects such as dam construction or conversion of a scheme to piped and pressurized irrigation, guarantees could be provided against: (i) contractual risk (payment risk, performance risk, etc.); (ii) regulatory risk (change in law, negotiation or cancellation of license, tariff adjustments, etc.); (iii) currency risk (convertibility, transferability); or (iv) political risk (expropriation, war, and civil disturbance, etc.). The box *A MIGA guarantee for irrigated date palm production in the Jordan Valley* illustrates how a guarantee can underwrite lending and investment in even the most difficult of contexts. However, attempts to expand the use of such guarantees in irrigation have been limited – one initiative to use a MIGA guarantee for irrigation modernization in Maharashtra fell through because government considered it too expensive an option.

At the level of credit to irrigators, one good example is from Tanzania, where the Tanzania Agriculture Development Bank (TADB) has offered credit guarantee schemes since 2018. TADB provides guarantees to finance institutions or partner banks to cover the risk of default on credit for smallholder farmers' irrigation equipment and inputs. This has been a success as the default rate is very low.[17]

A MIGA guarantee for irrigated date palm production in the Jordan Valley

MIGA guarantees are well-suited to mitigating the non-commercial risks of agribusiness investments, thereby lowering the cost of capital and helping secure financing. MIGA insures foreign direct investments against losses related to (i) currency inconvertibility and transfer restrictions; (ii) expropriation; (iii) war, civil disturbance, terrorism, and sabotage; (iv) breach of contract; and (v) non-honoring of financial obligations.

In the highly risky Occupied Territories, MIGA administers the West Bank and Gaza Investment Guarantee Trust Fund, which is providing investment guarantees of $4.8 million to a consortium of Palestinian investors for the development of two Medjool date palm farms in Jericho.

The farms will be the area's first large-scale cultivation project for Medjool dates and will help revitalize the West Bank and Gaza's agriculture sector. An estimated 20 percent of the project's production will be supplied to the local market. The remaining 80 percent will be exported mainly to Europe, contributing to the West Bank and Gaza's foreign-exchange earnings.

Source: MIGA Brief: Cultivating Agribusiness Growth

3.2.2 Risk management through farmer insurance

Farmer risk management strategies will be increasingly necessary as climate threats increase.

Risk management instruments such as insurance can not only underwrite farmer borrowing but can provide incentives for farmers to develop better risk management strategies and to reduce risk exposure.

In order to reduce lenders' risks, farmers may be able to buy insurance.

Farmers may insure – or be required by lenders to insure - the assets financed – for example, immovable assets such as irrigation infrastructure (on-farm tanks, dams, rainwater harvesting structures) or movable assets such as drip or sprinkler kits, solar pumps etc. Farmers may also be able to take out insurance against threats to their income stream, for example insurance against crop losses or weather insurance against weather hazards, which will underwrite the cash flow needed for debt service. Weather insurance is increasingly a focus as climatic

[17] Source: https://www.tadb.co.tz/wp-content/uploads/2020/07/SMALL-HOLDER-credit-Guarantee-scheme.pdf.

changes advance. Fortunately, new information technology is reducing risks and costs – see the box Risk management in agriculture through insurance.

Risk management in agriculture through insurance

Costs for agricultural insurances are generally relatively high and premiums are often heavily subsidized by governments. Out of 65 developed and developing countries, almost two-thirds subsidized premium costs with an average subsidy rate of 47 percent.

However, providing subsidized coverage for numerous small scale family farmers in developing countries is a massive challenge. New approaches such as weather-index-based insurances aim to address this challenge. The insurance holds when rainfall or temperature exceed or fall below specific thresholds, and measurements are taken by weather stations or satellite technology. This reduces assessment and operational costs for insurers, reducing the premium costs.

In India, for example, the Weather-based Crop Insurance Scheme covers over 13 million farmers for various climate risks. In sub-Saharan Africa, the *Agriculture and Climate Risk Enterprise (ACRE)* is the largest index insurance program among developing countries in which the farmers pay a market premium. It is the first agricultural insurance program globally to reach smallholders using mobile technologies. However, these programs still require public support through subsidies.

Recent studies show that for both index and conventional insurance applications, big data derived from current and new sources such as crowdsourcing, cell phone apps, satellite and radar-based imaging and drone-based imaging can be used to improve modelling and reduce the risks of providing insurance products to farmers.

One innovation is to adjust crop insurance premiums to reflect water holding capacity, and thus resilience to drought. Another is to vary premiums based on performance in order to provide incentives for sustainable water management.

Sources: Based on Laubenstein 2021 who cites multiple sources (q.v.); and on Transforming Agri-Food Sectors to Mitigate Climate Change: The Role of Green Finance. Nicoletta Batini, International Monetary Fund, nbatini@imf.org.

3.3 New sources of funds for irrigation modernization

3.3.1 Dedicated water investment funds

Dedicated water investment funds are financing irrigation projects around the world

Dedicated market-based water funds include the *Sustainable Water Impact Fund* co-developed by the Nature Conservancy's NatureVest and the investment firm Renewable Resource Group. The fund attracts capital from institutional investors with a traditional ten year fund structure to finance landscape-based approaches to protect water resources. With innovative elements, the fund balances the needs of a variety of water users, the environment and the fiduciary obligations for institutional investors. Launched in 2019, the initial offering closed in 2020 at $927 million. The Fund has already financed programs of several hundred million dollars. Initial projects have been in the US, Australia and Chile but expansion to other countries is envisaged.[18]

3.3.2 Relief projects and recovery funds

The COVID-19 crisis particularly impacted small-scale farmers, disrupting agricultural production and supply chains.
Many countries introduced a set of fiscal support measures to mitigate the immediate economic impacts of the crisis on the irrigation sector, including general financial support schemes, credit lines, loan guarantees, loan repayment moratoriums, and lower interest rate loans.

Immediate relief measures had the potential to strengthen farmers' resilience and to scale up self-financing, if well-targeted.

In Latin America, for instance, financial aid was channeled as direct economic support in the form of vouchers and bonuses to farmers in order to promote investments in small technical improvements in irrigation on a farm level. Israel responded with an increase in irrigation water quotas to boost agricultural production. Less positive were the temporary administrative and regulatory flexibilities introduced in some countries. These had potentially negative impacts on water quality and quantity and sustainable water management.[19] [Laubenstein citing OECD 2020].

[18] Source: Eric Hallstein, Deputy Managing Director, NatureVest, The Nature Conservancy. *Sustainable Water Impact Fund*: https://www.nature.org/content/dam/tnc/nature/en/documents/SWIF_ImpactReport_2020.pdf.

[19] Source: Marion Le Pommellec, Lead Specialist for Agriculture, Natural Resources and Rural Development, Inter-American Development Bank.

3.3.3 Ecosystem support funds and payment for ecosystem services[20]

Ecosystem support funds are collective investment vehicles which allow stakeholders to pool capital to finance improved water management or to pay for ecosystem services.

Through agreements, farmers are incentivized to improve specific natural resource management practices. They may, for example, be compensated for decreased fertilizer use and improved water management. The investments do not need to be repaid and investors do not get any direct return on investment. Instead, they benefit from the improvement in ecological services, for example improved water quality (see the box *Ecosystem support funds and payments for ecosystem services).*

Despite the complex nature of these mechanisms, they have largely proved effective in improving natural resource outcomes

Since the establishment of the first of these funds in 2000, more than 35 more funds have been set up in South and North America, Kenya and South Africa. They have proved an effective tool to tackle governance failures in multi-stakeholder settings and can mobilize multiple types of funding sources. Yet, development finance remains essential to support the set-up of these complex structures that bring together the needs of the various commercial actors as well as the different sources and expectations regarding returns.

Some of these funds have, however, experienced problems during times of economic crisis.

For example, in Peru the fund worked well for many years (see the box) but the impacts of the COVID crisis hit some utilities hard and they redirected cash from the fund to cover operational expenditures.

At a national scale, China has financed a massive ‘ecological compensation’ program that includes many aspects of agricultural water management.

This is a government-funded fiscal transfer program from the national government to subnational levels of government (and in some cases, onward to individual landholders). It covers a wide range of environmental problems, of which agricultural water management forms a significant part – see the box China’s ecological compensation program.

Ecosystem support funds and payments for ecosystem services

Water utilities or corporates with water-intensive activities and utilities such as breweries or beverage companies or other stakeholder have an interest in improving or conserving water quality and quantity, reducing their costs of water treatment or improving the quality of their products.

Success in Mexico

The brewery Heineken, for instance, invests in the Monterrey Metropolitan Water Fund (FAMM) in Mexico, which, to date, has leveraged $9.1 million to finance community-based water and environmental management upstream.

…..and in Peru

Peru has demonstrated success in ‘payment for environmental services’ (PES). In this approach, water utilities levy a charge on users to pay for upstream activities to conserve or restore ecosystem services. This provides a dedicated stream of funding for local community and civil society projects to protect water resources. To date, this mechanism has generated over $45 million which has been invested in ecosystem services in upstream communities.

…..and in Europe

Most of the water utilities in England and Wales, Eau de Paris in France, as well as the water companies Vittel-Nestlé and Volvic in France, have made agreements with farmers and compensate them for environmental services and sustainable water resource management.

Source; Laubenstein, drawing on material from multiple sources (q.v.)

[20] This section draws mainly on Laubenstein 2021.

China's ecological compensation program

At a national scale, China has financed a massive 'ecological compensation' program focused on soil and water conservation, mitigation of desertification and agricultural productivity and which includes many investments in agricultural water management. To date it has covered 625 million hectares of land and involved over 500 million people.

Environmental objectives are paired with poverty reduction and national food security goals. These efforts represent the largest such programs in the world, and while the challenges remain substantial, China has done more in absolute terms than any other country to reverse land and water degradation.

Source: China Trends and opportunities for incentive-based policies towards a greener China. World Bank 2021

3.3.4 Green Bonds

Green bonds are designated bonds intended to encourage sustainability and to support climate-related or other types of special environmental projects.
Green bonds finance projects aimed at energy efficiency, pollution prevention, sustainable agriculture, fishery and forestry, the protection of aquatic and terrestrial ecosystems, clean transportation, and clean water and sustainable water management. They also finance the cultivation of environmentally friendly technologies and the mitigation of climate change.

Globally, green bonds are now mobilizing $270 billion a year, with China and India – and the World Bank - amongst the leaders.

In 2019, a record $266.5 billion of green bonds were issued, and nearly $270 billion in 2020. Among developing countries, China and India have been major issuers. The World Bank is also a major issuer, raising $14.4 billion in green bonds from 2008 through 2020. The funds raised by the World Bank have been used to support 111 projects around the world, largely in renewable energy and efficiency (33%), clean transportation (27%), and agriculture and land use (15%). In irrigation, for example, green bonds helped finance the 2020 *Turkey Irrigation Modernization Project*, as well as irrigation efficiency and water resources management within the 2018 *Brazil Sergipe Water Project*.[21]

Chapter Four. Five essentials needed to move forward

The need for more investment in modernization is pressing and to move forward, work is need n five essential points. These five essentials are: (1) developing financial markets that are more adapted to the specificity of the investment and the investors; (2) developing new providers, new instruments and new sources; (3) ensuring that the investments are profitable and bankable; (4) generalizing FinTech and digital solutions; and (5) making sure that privately financed and privately executed and owned investment is responsible.

4.1 Adapting financial markets to the investments needed and the likely investors[22]

4.1.1 The inherent challenges of financing irrigation: Why has private finance been so slow to meet the market demand?

The specific character of irrigation makes it a difficult sector to finance
These specific characteristics include the large, slow yielding nature of infrastructure investments and their long payback period, and the generally poor bankability and high risk of agricultural investments and of individual farmers.[23] In addition, there are large externalities and public goods in the sector, and more generally a significant mismatch between public policy goals and the goals of investors.

Thus, from the financiers' viewpoint, investing in irrigation carries high risk and has a doubtful risk-return profile, partly because the investments tend to be relatively remote and often small

Irrigated agriculture is rural and often sited far from towns. In addition, many irrigated areas are physically fragmented, for example, individual farms which have their own water source such as a spring, an individual stream diversion, or groundwater. Where plots are gathered together in communal irrigation schemes, these are often small scale. Even where schemes themselves are large, individual farms and plots may be small – in the vast Mekong irrigated area for example, the average farm size is no more than half a hectare.

[21] Sources: (1) *https://www.investopedia.com/terms/g/green-bond.asp#toc-history-of-green-bonds); and (2)* World Bank: Bonds for Sustainable Development https://thedocs.worldbank.org/en/doc/273721524075859023-0340022018/original/investorpresentationibrdsir2018.pdf.pdf).

[22] This section draws extensively on World Bank 2022b: 13.

[23] As an example, the provision of collateral is problematic, as are the practicalities and costs of any repossession needed.

In addition, irrigation investments, particularly small scale ones, typically have poor 'bankability'

Bankers generally lack local knowledge or presence, and irrigation projects typically lack 'bankable' features. They are rarely prepared in the form of bankable projects. There is a marked lack of distinct revenue streams and assets that can be used as collateral and farmers typically have little or no profile to demonstrate their creditworthiness. Loan sizes may be small and transaction costs high. The challenge for a financier of appraising the risk of a small scale irrigation investment can be judged from the box: *The typical elements needed to build the risk profile of an irrigation investment*. [OECD 2020a: 5]

Even where larger scale projects are considered, investments may have poor bankability.

Irrigation investments are comparatively slow to yield benefits and so require medium or even longer term finance. The returns on investment may be relatively low, particularly where large scale infrastructure works are required, and the investment may not yield a cash flow adequate to service debt. [OECD 2020a: 8]

Box: The typical elements needed to build the risk profile of an irrigation investment:

- Is it easy to identify and track the borrower?
- Is the business plan realistic and will the cash flow service the farmer's obligations and leave a surplus?
- What are the production risks?
- What is the extent of climate risks?
- Is the technology proposed appropriate and accessible?
- Does the farmer have the right knowledge?
- Is the necessary working capital available?
- Are the correct quality inputs reliably available?
- Does the farmer have good access to profitable and assured markets?

Sources: World Bank 2022b; and OECD 2020a: 5

4.1.2 The continuing need for public investment

The implications are that public support is essential to improve access and achieve public policy objectives
Public support will be essential both to correct what is essentially a combination of failure in financial markets and to meet the need to ensure a complex of public goods and public policy objectives that cannot be met by purely private investment.

Fortunately, fiscal resources can often be freed up to finance these changes

Public support currently expended in misdirected subsidies can be repurposed to promote the development of financing for modernization. In Pakistan, for example it is estimated that up to US$ 9.1 billion (or 3.5 percent of 2020 GDP) of climate-damaging subsidies could be repurposed to build resilience, including to finance modernization and sustainable water management and farming practices in the irrigation sector. [Source: Pakistan Climate Change and Development Report 2022]

An approach that combines more than one public funding mechanism with other interventions is usually needed. For example:

- to support emerging financial markets or expand them into underserved areas, a combination of upfront grants and results-based financing can be applied.
- If farmers lack access to working capital financing but are otherwise close to being able to meet the lender's requirements, credit lines and risk mitigation can be considered.
- Where market-based solutions are not viable, demand-side subsidies can mitigate risks, or quite simply outright innovative public procurement and service delivery contracts with a view to building market viability.

4.2 Developing new providers, new instruments and new sources

4.2.1 Developing new providers

The challenge is to align the business models and incentives between public and commercial actors.
While private investors are mainly concerned by risks and returns, public funds are driven by public policy goals such as food security, poverty reduction or economic growth and look primarily at the economic and distributional impacts of an investment.

Governments are seeking to develop financial markets.

For example, in Rwanda – see the box *Rwanda's successful FLID financing program* in Section 2.4 above - there is an initiative to develop the private financing market by working with financial institutions to raise awareness and knowledge about irrigation and FLID and to develop fit-for-purpose financial products that could increase farmers' capacity to raise the co-payment and – over time – reduce Government's payment share in the FLID program.

Intermediaries can play an important role in broadening access to credit and in minimizing transaction costs.

Two of the major barriers to irrigation financing – the distance of financial institutions from farmers, and the high cost of dealing with smallholder lending – can be broken down by the use of intermediaries. Intermediaries with local presence and knowledge and with relations with potential borrowers can provide a bridge by bundling projects together (thereby making them big enough to attract the attention of financiers) and standardizing review processes (aligning project features with standard operating procedures in commercial banks). Financial institutions can thus work through locally-based SACCOs, or through projects or NGOs that can integrate financing options within broader support to irrigation modernization and agricultural development. [OECD 2020a]

4.2.2 Developing new instruments

Public funds and blended finance

Public funds, which have historically provided the lion's share of irrigation financing, can also play a very significant role in leveraging private finance.
Blended finance for modernization of large scale infrastructure has had limited application to date – see Section 3.1.1 above - but there is great potential. The power of blended finance for small scale and on-farm modernization is considerable – see the examples given in Section 2.3.2 above. Blended finance structures for smallholder modernization need to be tailored to the local context and farmers and water users need to be actively engaged. A clear structure with defined roles and good coordination of the different actors is crucial. [FAO 2021: 18, 61]

Further work on applying blended finance to irrigation could yield excellent results.

Challenges related to blending finance include the need for a good enabling investment environment, ensuring that development finance does not crowd out private finance, and ensuring that the desired development outcomes are realized. Further analysis is needed to draw lessons from experience with blended finance and better understand the challenges of applying the approach to irrigation.[24]

Integrated value chain approaches

One powerful de-risking method is to work with farmer organizations to take an integrated value chain approach

A number of innovative mechanisms have been devised to leverage finance for irrigation from value chains – see Section 3.1.3 above. These approaches can have the added advantage of integrating access to finance within broader market-based development. These approaches cluster farmers, connect them to high value and assured markets, and assist in accessing capital, tools and technologies. In this way, members of a co-operative or WUA collectively have better access not only to finance but also to market information, technical assistance and extension services and gain collective bargaining power. The power of collective action makes operations easier and cheaper, increases access to assets and services and lowers their cost. [World Bank 2022b: 23]

4.2.3 New sources

There is a growing number of investors and agencies interested in financing sustainable agriculture, including irrigation and there is potential for financing from the Paris Accords and subsequent agreements at Glasgow.

A number of new sources of irrigation finance have emerged in recent years – see 3.3 above – and numerous entities have expressed interest in providing funds to support irrigation modernization. A recent roundtable (FAO 2021) on financing sustainable use of water for agriculture attracted 375 participants, including private investors and financiers, multilateral and bilateral donors, governments, philanthropists, NGOs and research institutions. Among the new sources discussed at that roundtable was the Dutch *Fund for Climate and Development, FMO* – see the box below. This new fund links integrated improvements in agriculture and water management with aims of climate change mitigation and resilience-building. This highlights the potential for significant new financing for irrigation modernization within the framework of the Paris and Glasgow COP agreements. [FAO 2021: 2]

[24] The OECD is undertaking work to apply the OECD DAC Principles for Blended Finance to the case of water, to develop more tailored and actionable recommendations.

A new fund links climate goals with integrated agricultural development

The Dutch Fund for Climate and Development, FMO, combines short-term blended finance with long-term finance with grant elements, organized through strategic partnerships to place investments in mitigation and adaptation. An early project is aimed at improving farmer incomes in the sinking Mekong Delta and promoting a shift from irrigated monoculture to mixed rice-shrimp aquaculture ponds.

Source: Aart Mulder, Fund Manager, the Dutch Fund for Climate and Development

https://thedfcd.com/2022/05/04/wwf-and-dfcd-reverse-degradation-of-mekong-delta/

4.3 Ensuring that the investments are profitable and bankable[25]

Making investment in irrigation modernization credit-worthy requires profitability and income streams (i.e., value, and this may require investment beyond infrastructure or production).
New institutional or contractual arrangements may be needed, for example to develop public-private-producer partnerships (as has been done in Morocco). It may also be necessary to strengthen the value chain by, for example, developing input and output markets for high value irrigated agriculture or creating aggregation points through farmer producer organizations.

It may require devising income streams for non-market goods:

Approaches like PES may be needed to create incomes for farmers from good irrigation and drainage practices, or grants may be needed to support climate change mitigation through improved practices in irrigated agriculture.

Making profitable and bankable investments in modernization requires knowledge – what is the best investment and how can it best be acquired, financed and managed.

There is a case for public or broader industry involvement in disseminating knowledge and expanding engagement. Basic irrigation knowledge and related equipment standards are largely available. The challenges are to organize the segments of knowledge that are applicable to local conditions, develop or improve training and support centers, and then implement empowerment and support programs. A key element is for farmers to know how and where they can best access the financial support that they will need for modernization programs.[26]

Knowledge support networks for irrigation exist in most countries in the form of irrigation departments and extension services. However, selecting and financing irrigation modernization at the farm level require strengthened capacity building efforts. Several approaches are suitable in almost all countries:

- Strengthening the quality and breadth of specifications and performance standards in all government irrigation investment programs.
- Development and strengthening of private irrigation industry organizations – for example irrigation associations – which actively support education and certification and help farmers access financing.
- Establishing properly staffed, funded, and organized centers of excellence that can provide the proper mix of research, training, and technical assistance adapted to local farmers and farming conditions and help farmers to prepare bankable investments.
- To reach farmers and their organizations, excellent, simple, and pragmatic extension to help them make wise choices in preparing bankable proposals and in financing and purchasing equipment and in subsequent operation and maintenance.

General publicity and awareness can also be valuable.

An excellent example from the US is the *Irrigation Consumer Bill of Rights* (http://www.itrc.org/reports/icbr.htm), a three part document (General, Drip/Micro, and Soil/Plant Sensors) that was developed to improve the interaction between the irrigation dealer, financiers and the farmer.

4.4 Financial technology and digital solutions

Use of Fintech is a major opportunity to overcome the historical constraints of access to financial services for the poor.
Financial technology, or Fintech, is the use of digital technologies to improve financial services across all sectors. The main advantages of Fintech are reduced costs; reduced time engaging in transactions and increased speed in finalizing them; increased access to a wide range of users via user-friendly interfaces; added value through

[25] This section is based partly on the treatment in World Bank 2022b.

[26] The needs and how to best meet them are described in more detail in the technical fiche by Charles Burt attached to the I&M Guide (World Bank 2022a) Fiche 1.22 Setting up a system for irrigation design standards and knowledge.

more types of services in support of small, micro-, and medium enterprises; and administrative options for financial transactions and management for micro-savings, agricultural, and water user organizations.

Fintech, enabled by high uptake of smartphones can integrate irrigation operations with financial transactions.

Mobile phones are a dominant technology across world. In 2022, there are an estimated 7.26 billion mobile phone users globally, around 91% of the world population. Through the GSM network, Fintech services are accessible to farmers who are distant from regular banks and have limited finances, literacy and numeracy, and/or insufficient certification to hold regular bank accounts. The power of FinTech allows irrigation operations to be activated and billing and payment to be accomplished in real time by the simple use of a mobile phone – see the example in the box *GSM-enabled solar-powered pumps for small-scale farmers in Africa*.

Fintech platforms can also be used for credit assessment and appraisals

FinTech can help to assess capacity and constraints of all stakeholders in accessing finance, and can assist agencies in conducting systematic due diligence, and in establishing credit worthiness. Use of GIS, remote sensing and climate modelling can provide data on crop risks and potential force majeure conditions as well as loan repayment. [World Bank 2022b]

GSM-enabled solar-powered pumps for small-scale farmers in Africa.

Small irrigating farmers in Africa have access to solar pump services through their mobile phone, and they can pay for the services the same way. These are integrated, supplier-based financing arrangements (hire purchase or pay as you go). Pumps are activated through the GSM link and paid by the farmer using mobile money. These kinds of solutions can be extended to land preparation, post-harvesting, and other agri-tech services.

Source: World Bank 2021b

The digital app IrriTrack

In Uganda, an app ‘IrriTrack’ is used to develop and implement individual irrigation modernization plans.

IrriTrack tracks the farmer’s progress through the process of developing a modernization plan, acquiring irrigation equipment and arranging financing. The app enables farmer registration and data entry and provides tailored irrigation system sizing and cost estimations. The system then links the farmer automatically to suppliers and procurement – see the box Financing FLID in Uganda: Leveraging digital for tailored irrigation.

4.5 Ensuring responsible investment in modernization

It is essential to ensure that privately financed, privately executed and privately owned and managed investment in modernization is responsible because of the externalities and risks of harm to public interests.
There is a role for government in setting and implementing a legal and regulatory framework that ensures sustainable water resources management.

Although historically private and community institutions have regulated water rights and water development and management, these institutions are often ill-adapted to modern technology. This is particularly the case with groundwater exploitation which has seen a widespread ‘race to the bottom’, resulting in a form of the ‘tragedy of the commons. In addition, unmoderated private investment may have negative impacts on GHGs, forests and downstream users and environmental flows and responsible investment requires attention to soils, salination, drainage etc. There needs to be a legal and regulatory framework covering private irrigation and modernization programs. Water rights need to be clear and, particularly where water is scarce, a resource charge or other means of reflecting scarcity prices may be needed. One key point to watch with irrigation modernization is the paradox that more efficiency may lead to more consumptive use rather than less. Measures to monitor and control these effects are essential.[27] [FAO 2021: 7, 13]

Private investment in agricultural water also needs to fit within basin plans, agricultural development plans etc.

Investment in modernization cannot be carried out in isolation. It needs to be accommodated within plans for water and agricultural development at basin level. There is also a need to align investment in irrigation with water-related financing in infrastructure, roads, markets etc. [FAO 2021: 15]

[27] When this phenomenon occurred in the Morocco PNEEI, new measures for groundwater quotas and monitoring of consumptive use had to be introduced – see Section 2.1.4 above.

Financing FLID in Uganda: Leveraging digital for tailored irrigation solutions

Faced with increasing climate variability, Uganda is targeting irrigation development and in 2019 set up a program specifically targeting very small farmers, including women and youth. The main constraints facing these poor farmers are a very weak knowledge base unaffordable entry due to high equipment costs, exacerbated by an absence of micro-financing options.

In 2019, the Government created the *Micro-scale Irrigation Program* by inclusion of an irrigation window in the existing *Intergovernmental Fiscal Transfers Program for Results* (UgIFT). The Program supports farmers to purchase and use micro-scale irrigation equipment. The Government subsidy is 75% for solar-powered systems and 25% for petrol systems with a per ha ceiling that favors the simplest of technical choices. The program targets micro-irrigators up to 1 ha. Women farmers are actively included in their own right. The program covers a third of the country's districts and is facilitated by a cadre of district level technical and agricultural personnel.

The digital app IrriTrack

Central to the implementation has been training of staff on irrigation practices and technology, and on the IrriTrack App that was setup for the program. IrriTrack provides geo-referenced data collection and technical backstopping in the field. It tracks the farmer's progress through the process, enables farmer registration and data entry during farm visits (technical and enterprise choices), and provides tailored irrigation system sizing and cost estimations to help farmers decide on an affordable technical solution.

How the program works

Farmers are made aware of the program via multi-media channels including easy-to-read brochures and farmers' demo days. Farmers register their expression of interest via a local extension officer (using IrriTrack), and a farm visit is arranged. During the visit, field sizes are mapped, water sources assessed, land-tenure is confirmed, pumping requirements and crop choices are recorded. The farmer then explores technical and cost implications where the officer inputs technical irrigation preferences into IrriTrack, and preliminary sizing and costs are generated. Once a choice is finalized, data is uploaded into the Monitoring and Information System (MIS) and a technical sheet for each farmer is generated to aid suppliers and procurement. District procurement follows in batches.

Targets and achievement to date

Under the Uganda: *Intergovernmental Fiscal Transfer Project & Micro-Scale Irrigation Program*

Financing Modality, a US$ 50 million loan is expected to be matched by up to US$ 24 million of farmers' contribution to support irrigating farmers on less than 1 ha in gaining access to irrigation equipment.

In the first year, the program trained 650 staff, recorded the expression of interest by 22,700 farmers (a fifth of whom are women), tracked 8,700 farm visits (technical options and cost-estimation), recorded the approval of 5,900 procurements, and installed the first 137 irrigation systems.

Source: World Bank 2022c, based on a note by Gabriella Izzi gizzi@worldbank.org

Chapter 5. Looking ahead: Increasing the provision of finance for irrigation modernization

5.1 Towards a new role for government in financing irrigation modernization

Historically public finance and international transfers have predominated and there are good reasons why this has been the case.

Irrigation can be expensive, particularly for large modern schemes requiring extensive hydrological infrastructure where costs can be as much as $20,000/ha, well beyond the means of farmers. Hence, government financing and public subsidies have been common, even in high income countries – and this has proved an expensive drain on public resources.[28]

…..but there have been weaknesses resulting from high levels of public subsidy.

The high levels of investment subsidy have placed a huge burden on the public purse and often the burden has continued into the long term with continued O&M subsidies and low levels of recovery from users through tariffs, abstraction charges etc.

This predominance of public financing has crowded out private finance and has not been effectively leveraged to attract additional capital from private sources.

Overall, the high levels of public subsidy have tended to undermine incentives for accountability and performance, while the cheap provision of water for irrigation that has resulted from the high levels of subsidy has encouraged its over-use and pollution. [FAO 2021: 4]

In addition, at the country or basin scale, too high a level of subsidy can lead to expansion of irrigation that is uneconomic and detrimental to land and water resources.

[28] Public expenditures on irrigation range from 0.08-0.016% of GDP annually for MNA to 0.32-0.72% for SSA. [14.6]

Recent analysis (*Beyond the Gap*, World Bank 2021a) examined two models of public support to irrigation. The study found that where support was 'high, with all capital costs paid and no water scarcity price was applied, irrigation would tend to expand beyond economic limits, right up to the extent of the physically available water. However, where support was 'moderate' and water costs reflected the scarcity price, the irrigated area would only expand if it was economic at the level of the water economy and was profitable for farmers. [World Bank 2021a: 2, 3]

Essentially, the role of government needs to change

Overall, there is likely to be a trend in government involvement in irrigation financing towards the pattern in OECD countries – see Section 2.1.1 – in which governments invest in public goods and basin-level infrastructure, and the private sector and farmers invest in irrigation infrastructure and operations (within a clear regulatory framework).

Within this changed role of government, there is clearly a case for public financing - and for subsidies, but only if they are 'smart' and targeted

Key areas where there is a need or a comparative advantage for public financing include investment in public goods like water resources management, basin infrastructure, flood protection and the preservation of environmental flows. In addition, governments may invest in irrigation to pursue policy goals such as equity, poverty reduction, and inclusion, including gender inclusion, but these interventions need to be 'smart' – for example, aimed at correcting market failures in financial or product markets or at promoting environmentally sustainable cropping patterns and irrigation and production practices. In addition, there is a clear role for governments in R&D, institutional development and all aspects of training and capacity building. In more developed economies, public financing is already focused on these areas and developing economies are beginning to move in this direction. [14.1]

The United States provides an example of public financing of irrigation which is targeted at specific environmental and water resource management objectives – see the box *Irrigation District Financing in the United States.*

Irrigation District Financing in the United States

A majority of the irrigation infrastructure in the Western United States was constructed as a result of the 1902 Reclamation Act. Under the Reclamation Act, Congress authorized the construction of water projects to irrigate arid western lands. These construction projects were federally financed and provide water for irrigation and flood control, and for domestic, industrial, and municipal use. Many dams, reservoirs, and irrigation canals that were built as a result of this federal financing are still operational today.

Irrigation districts either have water rights or purchase water, and are responsible for conveying and distributing the water to individual fields. They are financially self-sustaining and non-profit – raising the majority of their funds through the sale of water and/or taxes on land. The legal structure of the irrigation districts and the very local nature of them (farmers pay the bills, and farmers are on the boards of directors, and frequent elections are held for board members) tends to stimulate a "can do" attitude.

Source: https://irrigationtoolbox.com/ReferenceDocuments/TechnicalPapers/IA/2004/IA04-1061.pdf

The current primary source of funding for irrigation modernization is from the Watershed and Flood Prevention Operations program (WFPO, PL83-566) from NRCS. The WFPO was created in 1954 to provide funding for projects constructed by local sponsors with cooperation from the federal government to "protect and restore watersheds up to 250,000 acres".

To be eligible, a project must have public sponsorship, impact area up to 250,000 acres, and provide benefits directly related to agriculture (includes rural communities) which are at least 20% of the project's total benefits.

Projects are eligible for up to $25 million in funding through WFPO. The WFPO program only requires a 25% match of federal funding rather than a 50/50 split which is typically required by government programs.

NRCS also offers the Regional Conservation Partnership Program for smaller projects. This program will pay up to a 50% match in funding. Other programs that offer small amounts of financing are offered by state and private organizations.

Project financing is available from the Watershed and Flood Prevention Operations program from the NRCS. Through this program, districts can receive up to $25 million for irrigation piping projects. NRCS also offers the Regional Conservation Partnership Program which can be used for smaller projects. This program distributes a pool of $300 million annually with up to $10 million for each project that passes the application process. Eligible projects must demonstrate innovative improvements to watershed and resource concerns.

Source: Based on a note by Palak Sharma, drawing on https://www.hydro.org/wp-content/uploads/2021/04/Irrigation_Modernization_with_Hydropower_Ziegler.pdf

5.2 What are the conditions to increase provision? What can governments do and what is the role of strategic partnerships?

Government can work together with stakeholders to strengthen the enabling environment for investment by developing clear policies governing irrigation development within broader natural resource management.

Three principal sets of policies are needed. The first requirement is for policies, regulations and institutions for water resources management and agricultural water management. Second is to put in place policies to ensure coordinated development, placing irrigation modernization within the economics and development of agriculture, trade, infrastructure, etc.

Finally, complementary policies are required to ensure incorporation of public environmental and social policy objectives e.g., to (1) ensure resource sustainability and use efficiency; (2) promote growth, equity, inclusion, and poverty reduction; and (3) strengthen climate-related resilience of systems and households. [OECD 2021a: 9, 14; FAO 2021: 7, 12, 72]

Governments need to have a smart and consistent public financing approach with a framework that supports private investment in irrigation.

Vital here is to have a consistent public financing approach that gives investors the confidence (including clarity on subsidy policy, on the roles of public v. private etc.). Also needed are measures to foster private financing of irrigation and to remove obstacles, including fostering PPP, blending, business-to-consumer financing (B2C) etc.

With these policies and frameworks in place, governments can develop a strategic financing approach in partnership with all stakeholders

On the government side, this would serve to define and plan the role and scope of public investment and subsidy for modernization, considering long term trends in demand – and risk (e.g., climate change). This would likely lead to a reorientation in public expenditure, for example a focus on: (1) repurposing subsidies and making them smart (subsidies will probably be needed, as they are even in high income countries); (2) investing in public goods like water resources management, basin infrastructure, flood protection, environmental flows; and (3) investing in human capital development and the knowledge agenda through R&D, training, institutional development and capacity building.

Governments should also work together with financial institutions, intermediaries and farmer organizations to strengthen financial markets and provision and devise appropriate instruments for both short term and long term financing specific to irrigation modernization, including high potential new approaches such as blended finance, risk sharing mechanisms, and value chain approaches. Special attention should be given to financing FLID, strengthening access and innovating financial mechanisms within integrated market development for smallholders.

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DEVELOPMENT AND PERFORMANCE OF SEMI-AUTOMATION SPRINKLE IRRIGATION UNDER DIFFERENT PUMP PRESSURES AND SPRINKLERS

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ABSTRACT

Decreasing of water resources in Indonesia impacted to agriculture production. In the other side, irrigation application system conducted by the farmers indicates a non-efficiency practice thus some efforts need to be made to solve the problem, especially to increase water use efficiency. This research was aimed to design an irrigation equipment which expected to make efficient use of limited irrigation water. The equipment was built based on sprinkle irrigation system in which a 25 m2 (5 m x 5 m) of platform was equipped. The platform contained 72 holes of micro sprayer. There were three types of micro sprinkler; octa-miter micro sprinkler (OM), Jet Spray 360 (JSF), Jet Spray 180 (JSH) which tested with 9 psi and 18 psi of pump pressures. The performance of the equipment assessed by indicators of diameter of coverage, discharge, infiltration profile, and coefficient of uniformity. The results reveal that different pump pressure significantly ($P < 0.05$) resulted on different diameter of coverage. The highest value of discharge was showed by 18 psi of pressure pump on JSF (10 ml. minute^{-1}). The infiltration profile reached a value of 100 cm of depth with the indication of depth inequalities.

Keywords: irrigation; sprinkle; performance; automation; water; efficiency

1. Introduction

Increasing of population growth was predicted slowly by 2030, however, there still enough people who will trigger the high demand of food supply in the next two decades (Lem *et al*., 2016). Climate and non-climate factors affect to production and non-production elements of food system which later contribute to the food security (Porter *et al*. 2014). Climate change brings several impacts on food production in term of water availability especially for plant uptake (Misra 2014; Rocha *et al*., 2020). In the future, the projection reveals the same pattern, as Boonwichai *et al*. (2018) projected that there was a rise trend of temperature and rainfall trend which significantly influence the paddy yield due to the water stress.

Some efforts were made to safeguard the green water in form of adaptation technologies which varied from agriculture cultivation technic, rehabilitation of natural resources from the impact of climate change, and social engineering to enhance community resilience (Widiyanti and Dittmann, 2014; Zhao *et al*., 2014, Al-Humaiqani and Al-Ghamdi, 2022). Irrigation technic and management as part of cultivation technic, however, have been developed and studied for a long time. Wu *et al*. (1986) had been revealed that hydraulic condition of emitters in trickle irrigation in practical point of view, is impossible to be obtained due to the variation of water pressure and manufacturing characteristics, however, it can be controlled by hydraulic design and manufacture's variations. Saad *et al*. (1996) developed model of trickle irrigation systems that was tested in citrus field resulted a smallest micro-sprinkler discharge, greatest area, a square field, and zero ground slope to produce greatest benefit. Irrigation automation, in line with the development of other irrigation technologies and management also has been expanded for a long time. In 1997, Luthra et al. developed an auto irrigation system which utilized modified manometer type tensiometer to control soil water tension. However, automation for irrigation design and system had been started long before. Hoekman (1971) designed telemetry control communication system to examined soil moisture, as a part of irrigation automation system. While Fisbach *et al*. (1970) had been developed control for automation irrigation system with reuse system with automatic controls were set in irrigation well and valve. Other research and work in the past related to automation for irrigation have been conducted for furrow and surface irrigation (Kruse et al. (1970); Myers et al. (1970).

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In the recent decade, automation on irrigation has been developing rapidly. Sensor combined with module and irrigation network has been widely developed (Ighrakpata *et al*., 2019; Gimpel *et al*., 2021; Liao *et al*., 2021; Rodriguez-Ortega *et al*., 2017). However, in developing countries, automation of irrigation needs to be suited with the economic and social conditions. Socio-economics barriers can be important factors determines the acceptances of precision farming technology related to fertilizer and irrigation (Blasch *et al*., 2022; Long *et al*., 2016). In Indonesia, as the same with other places condition, has a water shortage due to the climate condition (Pujiraharjo *et al*., 2015; Wijayanti, 2015) that lead to the water conflict issues (Suryo, 2019; Mardimin 2014). Hence, developing of an efficient smart irrigation system is needed to be conducted, especially to solve the water crisis in the off season and support the food supply in this current increasing population. This research was objected to develop an irrigation equipment with a better water efficiency to give an optimal water application.

2. Material and Method

2.1. Irrigation Equipment Design and Assembly

An irrigation equipment design was developed by addressing the field conditions. Since farmers commonly work in a quite small area of land, the tool was adjusted had a size according to the area of the farmer's plot. The equipment was planning to be automatically move from one to another plot based on soil moisture status. The amount of water in every irrigation application calculated from water availability in the soil and specified value of soil moisture status.

The equipment consists of two parts, i.e., rectangular platform as the main tool, and a track for the movement of the platform. In the first stage, the construction was just focused on the platform construction. The platform was built with simple materials that available in local markets and was constructed in a private workshop near the experimental field of Agriculture Faculty, Brawijaya University. It was needed about two months to design and construct the platform before tested it irrigation application performance.

2.1. Irrigation Performance Testing

The irrigation platform was designed in such a way that it allows emitters and sprinklers in varied types to be set according to the need of irrigation purpose. Principally the performance evaluation was charged for the emitters, sprinklers, piping system in the platform, and pump pressure. There were three types of micro sprinkler and two pressure value that were tested it performance. The types of micro sprinkler were octa-miter micro sprinkler (OM), Jet Spray 360 (JSF), Jet Spray 180 (JSH) while the pump pressures were set on 9 psi and 18 psi. From those type of micro sprinkler and pump pressure there was 6 combinations of pressure and type of micro sprinkler i.e., OM-18 psi, OM-9 psi, JSF-18 psi, JSF-9 psi, JSH-18 psi, and JSH-9 psi. The performance testing was repeated 3 times for each combination of micro sprinkler types and pump pressures.

Parameters of irrigation performance measured for all the combination were diameter of coverage, discharge, infiltration profile, and uniformity of application. The data was analysis statistically with T test with 95% of confidence intervals to distinguish the different of parameters between the types of micro sprinklers, emitters, and pump pressures.

3. Results and Discussion

3.1 Irrigation Platform

The irrigation platform constructed in this work has 5 m x 5 m dimension of width and length that is suited with 8 – 25 sq m, the range of paddy's plot area (Gomez, 1972). The size of this platform expected represents the farmer's plot and practically can be operated after its construction. There are two main parts of the platform, i.e., outer platform and inner platform. Outer platform was constructed as a frame for the equipment, while the inner platform consists of structure that will be embedded by an "iron rack". The iron rack is attached by eight of U shape bent iron in which along the iron HDPE (High Density Polyethylene) hose was adhered. The HDPE hose has 16 mm of inside diameter and in the base of U shape bent iron, nine emitters or micro sprinklers were sticked.

At the upper side of inner platform, plus-shaped iron plate was attached. This plus-shaped iron was set as a place of PVC pipe that functioned as sub-mine line in this system. Along the iron plate of upper inner platform, the mine line was extended and at every meeting point of the pipe and hose a tubbing adapter was set to connect it one each other. In this case, the HDPE hose roles as lateral.

The water was feed from the mine line in form of a flexible rubber hose with one inch of inside diameter that connected to the pump. In this mine line, there was a discharge meter to measure the water flow into the platform.

The inner platform completed by pulley system that can manage the height of the rack. The system was performed by a tackle set in the long iron plate that is attached in every corner of the outer platform. This system allows the inner platform to be positioned at a certain height, on the highest limit of plant canopy or in middle of plant height, depending on the need. Additionally, due to the objective for the platform to irrigate water for some agriculture plots, the whole platform was design to move from one to another plot. For this reason, the platform was fitted with four wheels. In this first stage, the wheels were constructed from rubber tire wheels due to the field condition that was muddy to allow the platform moved freely when testing was conducted.

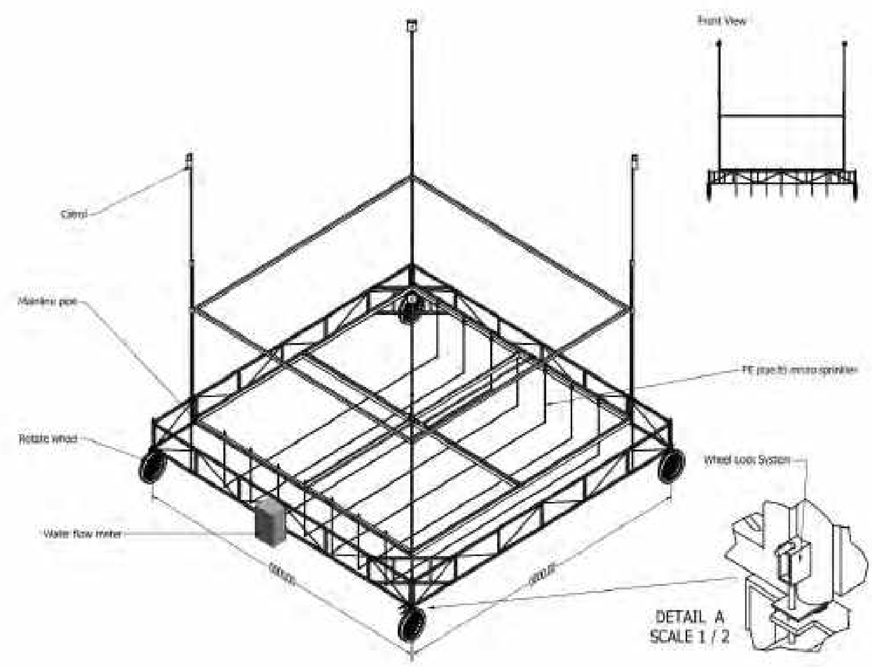

Figure 1. Design of irrigation platform

3.1 Irrigation Performance Indicator

3.1.1. Diameter of Coverage

Diameter of coverage, also call as wetted diameter is the distance in which sprinklers throw water perpendicular to the lateral. Wetted diameter of a sprinkler is very important in term of sprinkler selection and irrigation management (Bernuth *et al*., 1984). Wetted diameter of several sprinkler needs to be overlapped to obtain a better irrigation uniformity, and this will determine the maximum spacing between sprinklers (Brouwer *et al*., 2001). In this study, the 18 psi of pump pressure shown longer diameter of coverage compared to the 9 psi. This is reasonable because the high pump pressure resulted more energy to push and emit the water along the irrigation network and ended up in each sprinkler. Additionally, the widest diameter of coverage was found on JSH-18 psi and the lowest one was on OM-9. As JSH has half (1800) of coverage, the water with the same volume will flow through smallest hole and resulted on the longest water spray. In the other side, OM-9 had less pump pressure and micro sprinkler specification in which water in the head of micro sprinkler was distributed separated which produced the shortest diameter of coverage. Comparation for each combination with T test explains that only 27% of the total comparation was not significantly different on diameter of coverage (Tabel 1.)

Tabel 1. List of comparation between combination and its signification with T test ($p < 0.05$) on diameter of coverage

Comparation	Signif.	Comparation	Signif.	Comparation	Signif.
JSH-9 : JSF-9	s	JSF-18 : OM-18	ns	JSF-9 : JSF-18	s
JSH-9 : OM-9	ns	JSH-9 : JSH-18	s	JSF-9 : OM-18	ns
JSF-9 : OM-9	s	JSH-9 : JSH-18	s	OM-9 : JSH-18	s
JSH-18 : JSF-18	s	JSH-9 : OM-18	s	OM-9 : JSF-18	s
JSH-18 : OM-18	ns	JSF-9 : JSH-18	s	OM-9 : OM-18	s

s = significant; ns = not significant

The influence of pressure for the spray of coverage also had been researched. Jiang *et al*. (2019) used impact sprinkler with different nozzle types and different pressure to reveals the relationship between those two parameters. The result revealed that the augmentation of water pressure generated the larger of spray coverage of the impact sprinkler. However, in a certain case, the high pressure does not always follow with a high coverage as Ranta *et al*. (2021) found in sprayer machine, in which 5 bar pressure obtained higher degree coverage compared to the 9 and 7 bar pressures.

3.1.2. Discharge

Water flow from the source will be distributed in all the micro sprinkler in the HDPE line. Due to the arrangement of the sub-mine line and the position of water inlet, it suspected each micro sprinkler received different amount of water. Thus, the discharge in each micro sprinkler was evaluated. The result reveals that the average of discharge in 18 psi pump pressure higher than the 9 psi, with the values are 87 ml. minute-1 and 55 ml. minute-1, respectively. The highest amount of discharge was found on JSF-18 while the lowest one was on OM-9. The T test shown that there is 20% of comparation of combination that was not significantly different, as described in below table.

Tabel 2. List of comparation between combination and its signification with T test ($p < 0.05$) on micro sprinkler discharge

Comparation	Signif.	Comparation	Signif.	Comparation	Signif.
JSH-9 : JSF-9	s	JSF-18 : OM-18	ns	JSF-9 : JSF-18	s
JSH-9 : OM-9	s	JSH-9 : JSH-18	s	JSF-9 : OM-18	s
JSF-9 : OM-9	ns	JSH-9 : JSH-18	s	OM-9 : JSH-18	s
JSH-18 : JSF-18	s	JSH-9 : OM-18	s	OM-9 : JSF-18	s
JSH-18 : OM-18	s	JSF-9 : JSH-18	ns	OM-9 : OM-18	s

s = significant; ns = not significant

Water pressure hold a significant role for the discharge of micro sprinklers. This is in line with the research findings by Pachore *et al*. (2019) who tested several types of sprinklers in four of water pressure conditions. The result shown that the highest water pressure was operated in all the sprinkler types, the highest water discharge from the sprinkler. The relationship between pressure and water discharge is not only implemented on sprinkler. Kyada *et al*. (2013) revealed a similar result in which the increasing pressure generated the increasing of discharge in several types of drippers. The different range of water pressure between sprinkle and drip system indicates a wide range of water pressure values from small to medium pressure. However, the relationship between water pressure was consistent with the discharge. Additionally, the JSH micro sprinkler generate the highest amount of discharge compared to OM and JSF both on 9 and 18 psi pressures (Table 3).

Tabel3. Pressure and discharge data in several micro sprinkler types

Pressure (Psi)	Discharge (lph)		
	OM	JSH	JSF
9	2.6	5.7	3.4
18	5.1	8.3	3.6

3.1.3. Infiltration Profile

Infiltration profile is described as depth of water that flows into the soil profile after the irrigation application was conducted. The infiltration profile is determined only by the amount of water and the total area where the precipitation falls. The depth of infiltration profile, in this case, does not affect by soil properties especially on physical soil characteristics. The infiltration profile calculated in this research was regarding the value of water amount from each micro sprinkler. The difference is that the discharge is presented in form of two-dimensional graph in which the discharges was spread along the land's cross section. The result shown that octa miter resulted the lowest depth of soil infiltration profile. This means that the discharge emitted from this stuff was in the lowest amount and it is confirmed by discharge data. The pattern and depth of infiltration profile between JSH and JSF seems to be fairly. However, JSF give higher average value compared to the JSH. Related to the pump pressure, the 18-psi resulted deeper average of infiltration profile on JSH and JSF (Figure 2).

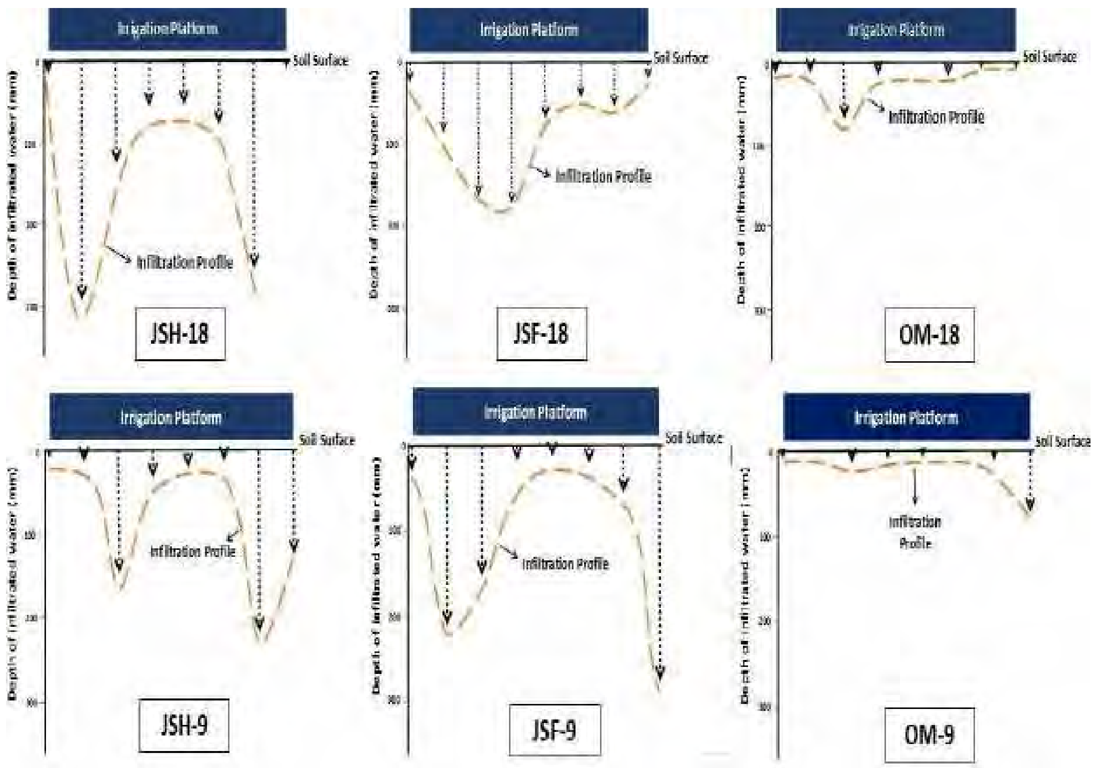

Figure 2. Infiltration profile in each type of micro sprinkler and pump pressure

3.1.4. Uniformity of Application

Uniformity in irrigation context is defined as the same amount of water application in each part of the irrigation area. It is the same meaning that uniform irrigation application allows all points, and all plants grow in the irrigation area get the same amount of water. The amount of water can be reflected from the depth of irrigated water in soil profile (Figure 2) as well as the index or coefficient of uniformity. Instead of uniformity, Figure 2 also informs about the adequacy of water applications. However, for the adequacy, it is necessary to includes soil physical properties, especially soil water holding capacity characteristics. The uniformity of micro sprinkler type and pump pressure combination in Figure 2 is shown mostly by OM-9 in which it shows the most evenness graph compared to the others. However, the depth of soil profile from this combination is very low so this will not be enough to meet the water need of any plants. The most probable combination is JSF-18 in which it has more water depth and more even line.

3. Conclusion

Different micro sprinkler and pump pressure show different response both diameter of coverage and discharge emitted by each micro sprinkler. The most compatible type of it should be detail studied by calculating the wetted perimeter resulted by the overlapping of diameter of coverage of multiple micro sprinklers. In this study, the 18 psi of pump pressure demonstrated the best in term of diameter of coverage, discharge, and the uniformity. Additionally, the JSF with full coverage of water emissions reflected the optimum value of performance. While the highest discharge obtained by the JSH micro sprinkler. However, this irrigation performance needs to be enhanced by reducing factors that lowering its irrigation performance. In line with those, some automation should be arranged in some parts of this platform to get the final aims of this platform construction.

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EFFECTS OF MAGNETIZED BRACKISH WATER DRIP IRRIGATION ON WATER AND SALT TRANSPORT CHARACTERISTICS OF SANDY SOIL IN SOUTHERN XINJIANG, CHINA

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ABSTRACT

Xinjiang is short of freshwater resources and rich in brackish water resources. However, the unregulated use of brackish water for agriculture leads to the aggravation of secondary salinization in soil. Magnetization can improve the quality of brackish water. To evaluate the effects of magnetized brackish water drip irrigation on water and salt transport characteristics of sandy soil in southern Xinjiang, China, a field plot experiment was carried out, in which irrigation water was treated using one or two water magnetization events at different magnetization intensities. Water was treated at five magnetization intensities, 1000, 2000, 3000, 4000, or 5000 Gauss (Gs), while unmagnetized water was used for the control. The results showed that the magnetization of brackish water used in drip irrigation increased the water holding capacity of the root layer soil. Magnetized irrigation water enhanced the leaching of soil salt and reduced the rate of salt accumulation. Compared with the control, the salt content of the magnetized water-irrigated soil decreased by 15.0%~33.7%, and the salt storage in the magnetized water-irrigated soil decreased by 44.99%~86.78%. The lowest rate of salt accumulation (4.96%) was observed at a magnetization intensity of 3000 Gs. Magnetized water irrigation changed the composition and proportions of soil ions, and the degree of Na^+, Cl^-, and SO_4^{2-} leaching in the soil was greater. The effect of magnetizing the irrigation water twice was greater than that of one magnetization event. Magnetizing the water twice at an intensity of 3000 Gs led to the largest decrease in the relative percentage contents of Na^+ and Cl^-, which were 80.90% and 82.36%, respectively. The total carbon content after irrigation with magnetized water increased by 13.48%~63.35%, and the total nitrogen content increased by 11.73%~147.96%. The magnetization intensity had a significant effect on the soil carbon and nitrogen contents, which showed of trend of first increasing and then decreasing as the magnetization intensity rose. The magnetization treatment of irrigation water can therefore reduce the risk of soil salinization and reduce salinity stress on crops in arid regions, providing a new method for alleviating the shortage of freshwater resources in Xinjiang and a means to use brackish water safely, while improving salinized soil.

Keywords: Magnetized brackish water; Water salt distribution; Salt accumulation; Salt ions; Soil carbon and nitrogen

1. Introduction

The shortage of freshwater resources and soil salinization are the main limiting factors for agricultural development in China (Zhou et al., 2022). Xinjiang, located in the northwest of the country, has one of the widest distributions of saline alkali land in China. The saline alkali region is about 20 million ha, is mainly distributed in the south of Xinjiang, and accounts for about 1/8 (12.5%) of the land area of Xinjiang and 1/4 (25%) of the plain area. It is internationally known as the "World Museum of Saline Alkali Land" (Wang et al., 2019a). The southern Xinjiang oasis agricultural area is mostly distributed on the edge of the Taklimakan Desert, located in an arid inland region, with little rainfall and strong evaporation, and forms a typical "desert oasis, irrigated agriculture" area. The land is affected by factors such as the salt content of the soil parent material, the unregulated use of brackish water irrigation, high salinity of the groundwater, and the large evaporation ratio. Long-term drip irrigation has gradually increased the soil salt content, aggravating the risk of secondary soil salinization and seriously restricting the sustainable development of agriculture in Xinjiang (Zhang et al., 2013). Therefore, seeking to alleviate the shortage of freshwater resources and improve soil salinization has become an important proposition for the sustainable development of agriculture in Xinjiang.

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As new technology for use in agricultural irrigation, magnetized water irrigation shows great potential for application in agriculture and forestry (Wang et al., 2020; Ali et al., 2014). Magnetized water mainly refers to water standing in or passing through a magnetic field of a certain intensity vertically or horizontally at a certain velocity. The former is called static magnetized water, and the latter is known as dynamic magnetized water (Zhou et al., 2012). After magnetization, the physical and chemical properties of irrigation water change significantly (Pang et al., 2008), such that the hydrogen bonds of the water molecules become weak, the surface tension of the water decreases, the infiltration capacity increases (Sheng et al., 2021), the viscosity of the water molecules decreases (Ghauri et al., 2006), the association coefficient decreases (He et al., 2014), the conductivity and pH value increase, the dissolved oxygen content increases (Wang et al., 2016a), and the original macromolecular group becomes a single and active small molecular group (Wang et al., 2018). Changes in the physical and chemical properties of magnetized water cause the water molecules to be more permeable and soluble during migration, which can promote the dissolution of minerals in the soil and improve the availability of soil nutrients (Wang et al., 2018).

Previous studies have shown that magnetized water irrigation can effectively promote the leaching of salt in soil, which provides a new idea for improving soil in saline alkali areas. Magnetized water irrigation can effectively promote salt leaching in cotton growing regions; when the magnetization intensity was at 4000 Gauss (Gs), the soil desalination rate, cotton yield and water productivity were found to be the highest (Zhou et al., 2022). Magnetized water irrigation can promote the downward movement of soil salt and increase the leaching of chloride and sodium ions (Zhang et al., 2013). Furthermore, Liu Xiumei et al. (2016) demonstrated that magnetized brackish water irrigation increased the absorption and utilization of soil nutrients by crops, and Mostafazaden et al. (2012) showed that magnetized water irrigation can leach more base ions than untreated water. In fact, Bu Dongsheng et al. (2010) concluded that the contents of Cl^- and SO_4^{2-} in the 0-60 cm soil under drip irrigation with magnetized water decreased significantly. Su Jie et al. (2007) revealed that magnetized water irrigation improved the activities of catalase, amylase and other enzymes in the soil, and Wang Lu et al. (2016b) showed that magnetized water irrigation treatment can effectively promote the growth of jujube trees, increase the contents of macroelements and microelements in leaves, and improve the availability of soil nutrients. Peng Yao et al. (2019) concluded that, compared with unmagnetized treatment, magnetized water irrigation significantly increases the soil desalting rate and cotton yield, while Zheng Deming et al. (2008) showed that magnetized water irrigation reduced the solubility of soil soluble salts, and soil salt content decreased with the increase in the number of times the water was magnetized.

In general, magnetized water irrigation can, to a certain extent, promote leaching of soil salt and reduce salt stress in crop roots, which is of great significance to the improvement of saline-alkali land. However, the mechanism of soil desalination under magnetized water irrigation is still unclear. The movement and distribution of soil water and salt, the amount of soil salt leaching, and changes to the levels of base ions in soil solution under different magnetization intensities and depending on the number of times the water is magnetized are still unclear. To address this issue we: (i) investigated the influence of magnetized brackish water drip irrigation on water and salt transport characteristics of soil in a sandy area of Xinjiang, (ii) analyzed the water and salt transport distribution and desalination characteristics of soil under magnetized brackish water irrigation, and (iii) explored the best use of magnetized water technology for brackish water and saline alkali land improvement. The findings provide information for promoting saline-alkali land improvement and ecological recovery of the oasis irrigation area in Xinjiang, China.

2. Materials and methods

2.1 Experimental site

The experiment was conducted at the Irrigation Test Station of Pimo Reclamation Area, Kunyu City (37°12′N, 79°17′E, altitude 1458 m, average ground slope 5.4%) from April to November 2021 in Xinjiang, China (Figure 1). The experimental site is in an arid inland area, typically known as a "desert oasis, irrigated agriculture" region. The area has an annual average rainfall of 61.5 mm, annual average evaporation of 2487 mm, evaporation-rainfall ratio of more than 30, an active accumulated temperature above 10℃ of 4208.1℃, an annual average atmospheric temperature of 12.2℃, and 2769.5 h of sunshine annually. The frost-free period lasts for 244 days. The annual average number of dusty days is about 220 d. Air temperature, precipitation, wind speed, and other meteorological data were recorded by an automatic weather station located 100 m from the study site.

The soil at this site is sandy loam with a pH of 7.88. The depth of groundwater is about 3.0 m, and the maximum depth of frozen soil is 0.67 m. Due to strong evaporation, the problem of soil salinization in this area is serious. The meteorological data during the growth period of jujube is shown in Figure 2. Within the 0-40 cm topsoil, the organic matter, total N, and available P and K are 4.23 g kg^{-1}, 4.82 mg kg^{-1}, 17.61 mg kg^{-1}, and 84.52 mg kg^{-1}, respectively. The physical characteristics of the soil (dry bulk density and field water holding capacity) in different soil layers (0-140 cm) are shown in Table 1.

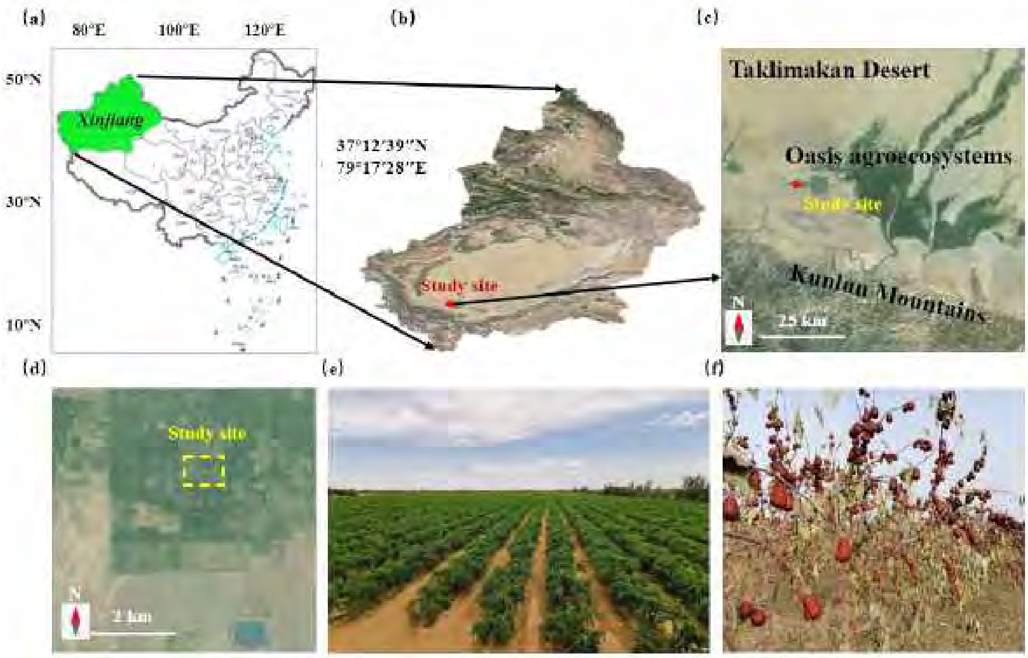

Figure 1. Maps and imagery of the study site. Xinjiang is located in the northwest of China (a) and is characterized by an extremely arid desert climate (b). High levels of agricultural irrigation are required for the oasis agroecosystems in Xinjiang (c). Field experiments were conducted at the Irrigation Test Station of Pimo Reclamation Area (37°12′N, 79°17′E) in Kunyu City, Xinjiang (d-f).

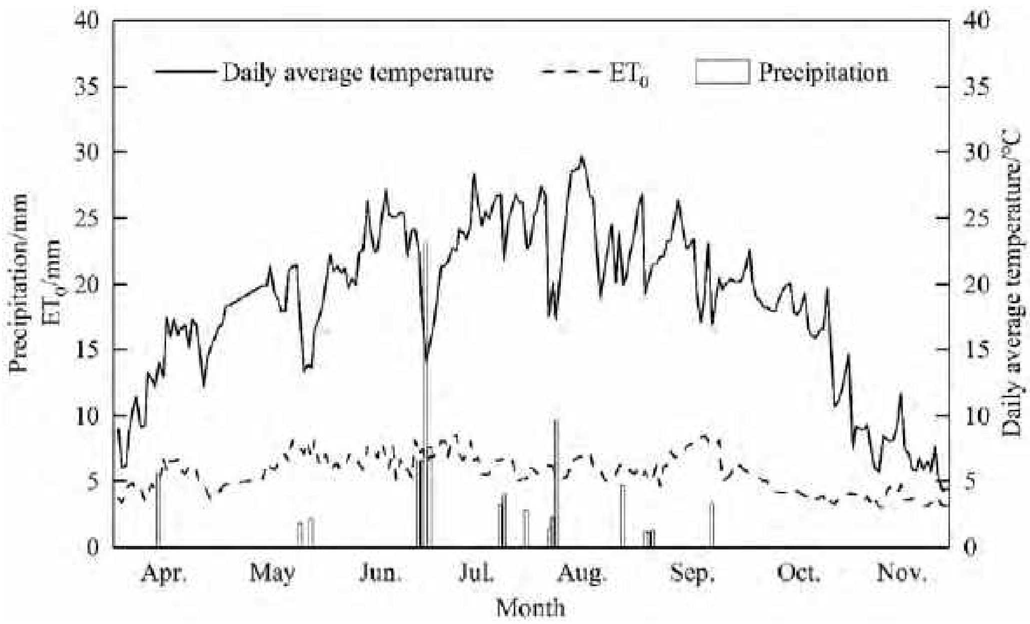

Figure 2. Daily average temperature, daily precipitation, and ET_0 (reference crop evapotranspiration) during the jujube tree growing season at the Pimo Reclamation Area experimental site in 2021.

Table 1 Particle composition and physical properties of soil layers in the test area (soil dry bulk density and field water holding capacity)

Soil depth (cm)	Soil texture	Percentage of sand (2-0.02 mm) /%	Percentage of silt (0.02-0.002 mm) /%	Percentage of clay (<0.002 mm) /%	Dry bulk density /(g·cm^{-3})	Field water holding capacity/%	pH
0-20	Sand	89.58	4.69	5.73	1.58	31.28	7.76
20-40	Sand	74.66	13.00	12.35	1.61	30.91	7.72
40-60	Sand	69.58	16.83	13.59	1.61	39.22	7.69
60-80	Sand	63.66	31.73	4.61	1.60	45.57	7.56
80-100	Clay	44.37	4.21	51.42	1.54	31.37	8.15
100-120	Sand	68.92	26.76	4.32	1.77	52.96	7.46
120-140	Sand	73.09	23.47	3.44	1.80	54.22	7.45
Average value	/	69.12	17.24	13.64	1.64	40.79	7.68

2.2 Experimental design

The random block design was used based on number of magnetization events and magnetization intensity. The research objects were 12 dwarf, densely-planted jujube trees. The number of times water could be magnetized was set to two, and the magnetization intensity was set to five levels: 1000, 2000, 3000, 4000, and 5000 Gs. The unmagnetized treatment was set as the control (CK). There were 11 treatments (Table 2), with three replicates for each treatment, and a protection row between each treatment. There were 33 experimental plots in total, each with a length of 38 m, a width of 4 m, and an area of 152 m^2 (with an area >130 m^2 meeting the requirements of the specification).

The experimental magnetizer was a permanent agricultural magnet produced by the Inner Mongolia Baotou Magnetic Materials Factory. The permanent magnet was made of sintered Ru iron boron. Magnetizers of different magnetization intensities were fixed to the water supply pipe, vertically to the flow, from pole N to pole S. When the irrigation water flowed through the magnetizer, magnetized water with different magnetic intensities was obtained. A Gauss meter was installed at the end of the pipe to monitor the magnetization of the irrigation water. A schematic diagram of the magnetization system installation in the field plots can be seen in Figure 3.

Table 2 Combination design of experimental scheme

Level factor	Experimental factors		Experimental treatment
	Magnetization frequency (M)	Magnetization intensity（G/GS）	
0	0	0	CK
1	1	1000	M1G1（T1）
2		2000	M1G2（T2）
3		3000	M1G3（T3）
4		4000	M1G4（T4）
5		5000	M1G5（T5）
1	2	1000	M2G1（T6）
2		2000	M2G2（T7）
3		3000	M2G3（T8）
4		4000	M2G4（T9）
5		5000	M2G5（T10）

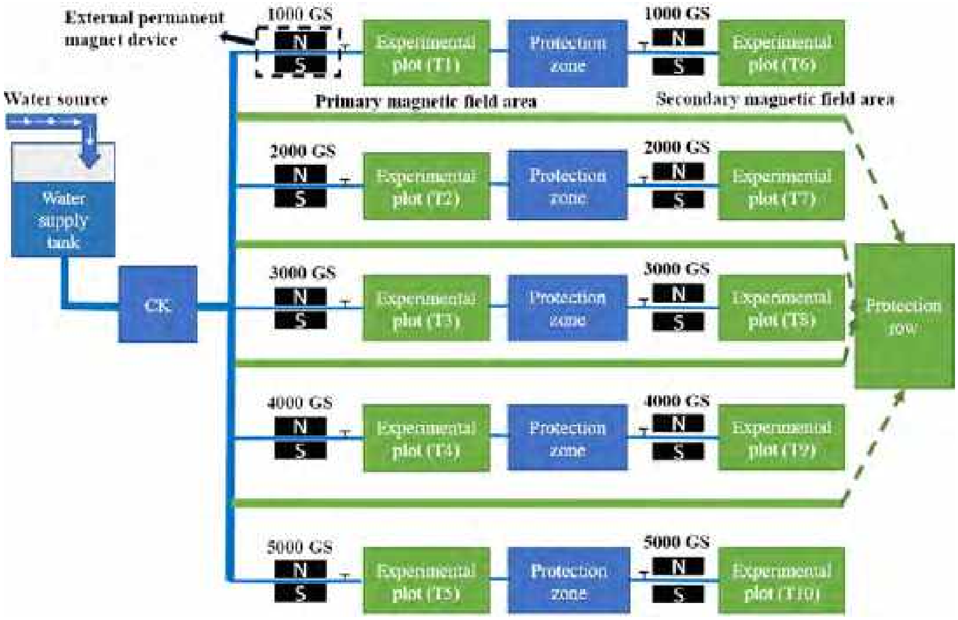

Figure 3. Schematic diagram of magnetization installation and layout in field plots

The dwarf dense planting mode was adopted for the jujube trees (Figure 4). The row spacing was 4 m and the plant spacing was 1 m. The plant height was about 2.4 m, and the theoretical planting density was 2500 ha^{-1}. The arrangement of drip tapes was one row of jujube trees to two drip tapes, which were located 20 cm to each side of the trees. The drip irrigation capillary was a single-wing labyrinth thin-walled drip tape. The distance between the drippers was 30 cm, and the emitter flow rate was 2.6 L h^{-1}. The water supply system in the study area was mainly formed of self-pressure irrigation, with the pressure and regulating valve installed at the head of the system. The amount of irrigation, irrigation dates and frequencies, and fertigation frequencies for all treatments were the same throughout the experiment. The irrigation quota was 6750 m^3 ha^{-1}, and the salinity of irrigation water was generally between 1.6 and 3.0 g L^{-1}. The jujube trees were irrigated 11 times during the whole growth period. The irrigation interval was about 14 days: twice during the budding and new shoot stage, three times during the flowering period, three times during the fruit expansion stage, twice during the white ripening stage, and once during the mature stage. According to local fertilization experience, N fertilizer was applied at 342 kg ha^{-1}, P_2O_5 fertilizer at 171 kg ha^{-1}, and K_2O fertilizer at 257 kg ha^{-1} during the whole growth period. The fertilizer was dissolved in the water used for irrigation. The details of irrigation and fertilization management during the growth period are shown in Table 3. The jujube planting mode is shown in Figure 4.

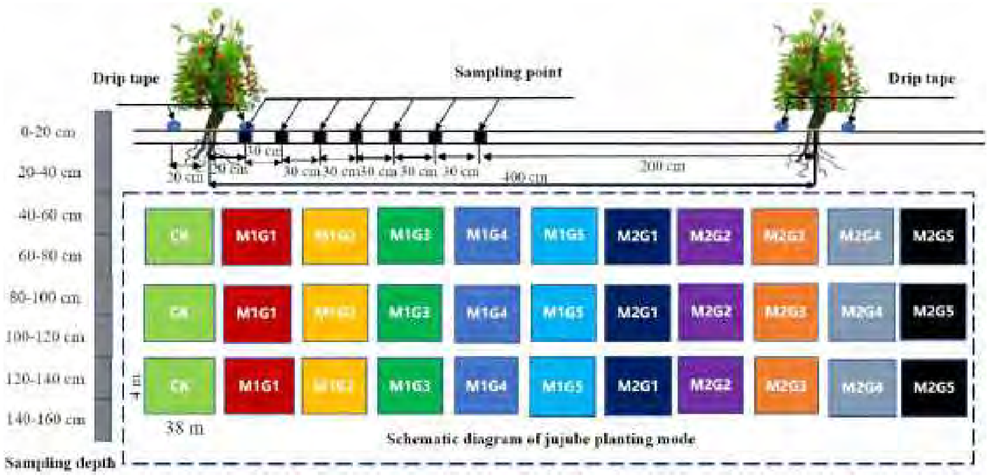

Figure 4. Schematic diagram of jujube planting mode

Table 3 Irrigation schedule during the jujube growing season in 2021

Growth stage	Irrigation date	Irrigation quota（m^3/hm^2）
Budding and new shoot stage	April 25, 2021	560
	May 9, 2021	560
Flowering stage	May 23, 2021	600
	June 6, 2021	600
	June 20, 2021	600
Fruit expansion stage	July 4, 2021	650
	July 18, 2021	650
	August 1, 2021	650
White ripening stage	August 15, 2021	630
	August 29, 2021	630
Maturity stage	September 12, 2021	620

2.3 Sampling and field measurements

2.3.1 Soil water content

Soil moisture was measured to a depth of 160 cm at 20 cm intervals during different jujube growth periods by drying and weighing the soil. The sampling point was between 0 and 180 cm away from the drip tape. There were seven sampling points in the vertical drip irrigation belt at intervals of 30 cm (Figure 4). Soil was removed by drilling a hole, which was then backfilled with fine soil. Soil samples were collected using a stainless-steel ring knife (100 m^3). Three replicate soil samples were taken from each sampling point, corresponding to the horizontal position. These soil samples were oven-dried to a constant weight to calculate the gravimetric soil moisture. The volumetric soil moisture content was calculated based on the measured gravimetric soil moisture and soil bulk density. Soil water storage was calculated to a depth of 0–160 cm.

Soil water storage refers to the amount of water stored in a certain area and soil layer. The water storage (C) per unit area (1 m^2) of soil mass at a certain depth was calculated as (Li et al., 2015):

$$C = 10\gamma_i h_i \theta_i, \qquad (1)$$

where, *C* is the soil water storage at a certain depth (mm); γ_i is the soil bulk density of layer i (g cm^{-3}); h_i is the soil thickness of layer i (cm); and θ_i is the gravimetric soil moisture of layer i (%).

2.3.2 Soil salinity and soil desalination rate

Soil samples before irrigation and at different jujube growth stages were taken to measure soil salinity. The oven-dried soil samples were pulverized and passed through a 1 mm sieve. Then, 20 g of soil powder were taken from each sample and mixed at a ratio of 1:5 with water. After being shaken evenly, the mixture was set aside for 2 h. The electrical conductivities ($EC_{1:5}$) of the mixtures were measured using a portable electrical conductivity meter (DDS11-A, manufactured by Shanghai Leichi, China). The residue drying mass method was used to calibrate the total amount of water-soluble salts in the soil. The calibration equation for electrical conductivity and salt content was y = 1.5984x−0.37 (R^2 = 0.96; n = 21) (Figure 5). The salt storage (S) per unit area (1 m^2) of soil mass at a certain depth was calculated as (Li et al., 2016a):

$$S = 10\gamma_i h_i y_i, \qquad (2)$$

where, S is the soil salt storage (g); γ_i is the soil bulk density of layer i (g cm^{-3}); h_i is the thickness of layer i (cm); y_i is the soil salt content of layer i (g kg^{-1}).

Soil desalination rate:

$$P = \frac{S1-S2}{S1} \times 100\%, \qquad (3)$$

where *P* is the desalination rate (%); *S1* is the initial salt content of the soil before irrigation (g/kg); *S2* is the soil salt content at the end of the jujube growth period. $P > 0$ represents soil desalination; $P < 0$ indicates salt accumulation in soil; $P = 0$ means the amount of soil desalting is equal to the amount of accumulated salt, and the salt content is in equilibrium.

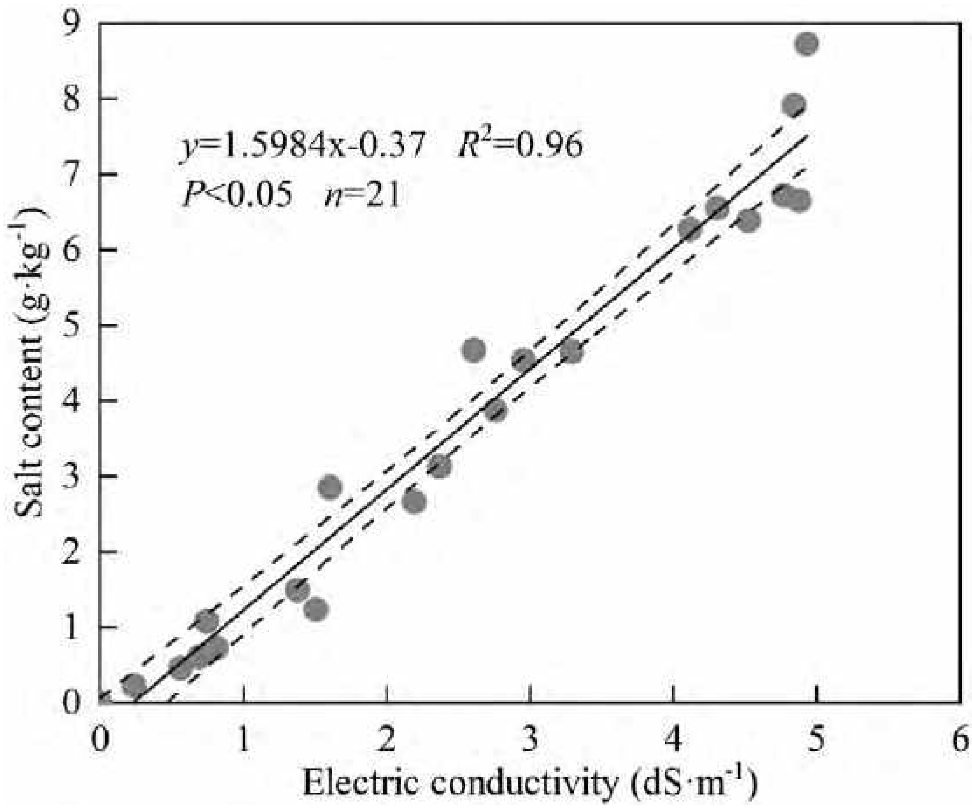

Figure 5. Relationship between soil salt content and conductivity (*$EC_{1:5}$*)

2.3.3 Soil salt base ions

The sampling time and location were the same as those used for testing soil moisture. The method of determining sample ions are from Li et al. (2016b). The Ca^{2+} and Mg^{2+} concentrations were determined by EDTA titration, Na^+ and K^+ by flame photometry, CO_3^{2-} and HCO_3^- by double indicator-neutralization titration, Cl^- by silver nitrate titration, and SO_4^{2-} by EDTA indirect complexometric titration. The results were converted to the same unit (g/kg). The above measurements were repeated three times for each treatment, and the average value was taken.

2.3.4 Soil total carbon and nitrogen contents

The soil total C and N contents were measured to a depth of 160 cm at 20 cm intervals during different jujube growth periods. The air-dried soil sample was ground through a 0.1 mm sieve, and then a 100 mg soil sample was wrapped in tin foil and weighed using a balance with 1/10,000 accuracy. The total N and C contents of the soil were determined using a CN-802 system (VELP, Monza, Italy). The total C was determined by the nondispersive infrared method and the total N was determined by the Dumas combustion method.

2.4 Statistics and analysis

The experimental data were graphed and processed using Origin 9.0 and SPSS 20.0. The SAS package (SAS Institute Inc., Cary, NC, USA) was used to conduct the analysis of variance (ANOVA). Differences were considered statistically significant when $p \leqslant 0.05$.

3. Results

3.1 Soil volumetric water content

Soil water content during crop growth significantly affected cotton final crop yield. The effects of different magnetized water treatments on soil volumetric water content during the growth period of jujube are shown in Figure 6. The change trend of average soil volumetric water content in the 0-160 cm soil layer irrigated with once magnetized and twice magnetized water during the growth period of jujube was the same, which was to increase first and then decrease over the growth period. The water requirement of jujube at the germination and new shoot stage was small, and the irrigation amount and irrigation frequency were low, so the soil water content at the germination and new shoot stage was low. Over the course of the growth period, the water requirement, irrigation frequency, and irrigation amount increased, and the soil water content gradually increased to reach a maximum at the fruit expansion stage. During the maturity stage of jujube, sugars began to accumulate, and the water demand decreased. With the decrease in irrigation water, the soil water content gradually decreased.

Comparing and analyzing the soil water content following one (M1) or two (M2) magnetization events, the average soil volume water content after one magnetization and two magnetized water irrigation with different magnetization were 20.2%, 20.8%, 24.7%, 23.4%, 21.3% and 21.4%, 21.9%, 25.5%, 24.5% and 22.6%, respectively. The average volumetric water content of soil following M2 was greater than that following M1 under the same magnetization intensity, while under magnetized water irrigation it was greater than under the non-magnetized treatment. The average soil volumetric water content under each magnetization intensity was in the order: 3000 Gs > 4000 Gs > 5000 Gs > 2000 Gs > 1000 Gs > 0. When the magnetization intensity was 3000 Gs, the soil volumetric water content was the maximum, and when the intensity was 0 Gs, the average soil volumetric water content was the minimum. Compared with the unmagnetized treatment, the average volumetric water content of soil treated with 1000 Gs, 2000 Gs, 3000 Gs, 4000 Gs, and 5000 Gs under M1 and M2 conditions increased by 9.8%, 13.0%, 34.2%, 27.2%, 15.8% and 16.3%, 19.0%, 38.6%, 33.2%, 22.8%, respectively.

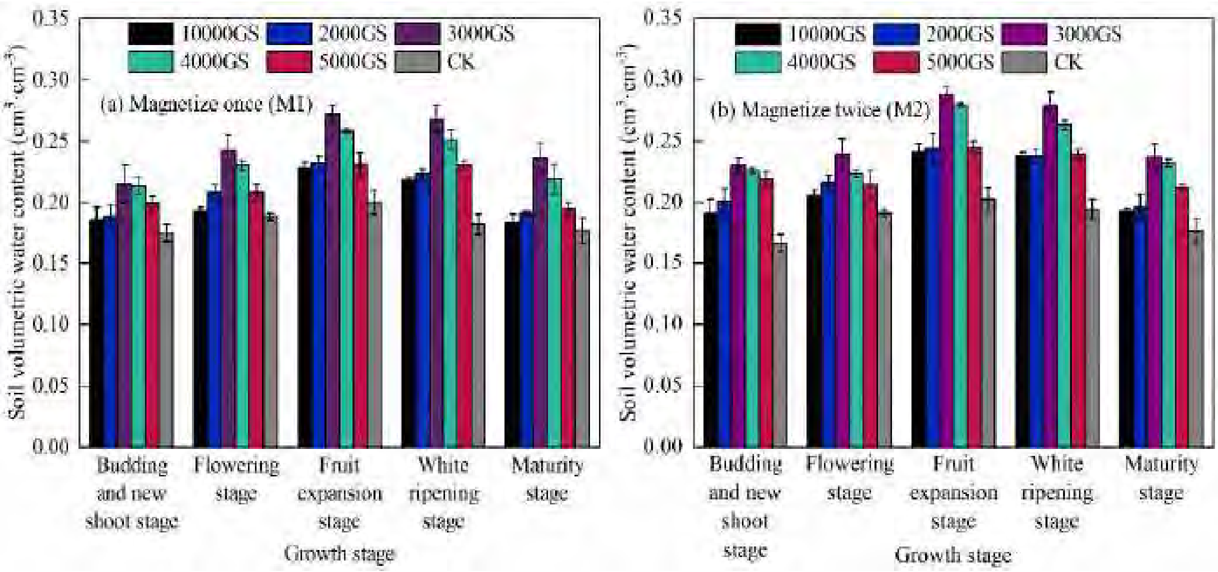

Figure 6. Changes in soil volumetric water content during the growth period of jujube treated with magnetized water drip irrigation.

3.2 Cumulative change in soil water storage before and after drip irrigation with magnetized water

The cumulative change in the average capacity to store water in different soil layers was measured 48 h after irrigation with water following different magnetization treatments during the fruit expansion stage (Table 4). Table 4 shows that the cumulative change in soil water storage capacity in different soil layers under magnetized water irrigation was greater than that under unmagnetized water irrigation. The average water storage capacity in the 0-80 cm and 0-120 cm layers of soil irrigated with magnetized water was significantly higher than that of soil treated with unmagnetized water, and the difference between the 0-160 cm soil treatments was small. The amount of infiltration and the downward movement rate were reduced when soil was irrigated with magnetically-treated brackish water.

Analyzing the change in the average soil water storage capacity in the 0-80 cm soil layer under M1 and M2 treatments showed that magnetization of water at 1000 Gs, 2000 Gs, 3000 Gs, 4000 Gs, and 5000 Gs increased the soil water capacity by 9.14%, 11.09%, 39.24%, 39.55%, 12.88% and 16.90%, 22.67%, 49.27%, 51.80% and 23.74%, respectively, compared with the unmagnetized treatment. Compared with the unmagnetized treatment, the average soil water storage in the 0-120 cm layer increased by 12.53%~51.86% when irrigated with magnetized water, and the average soil water storage in the 0-160 cm soil layer changed only slightly. Under the same number of magnetization treatments, the soil water storage capacity in the 0-80 cm and 0-120 cm layers was in the order: 4000 Gs > 3000 Gs > 5000 Gs > 2000 Gs > 1000 Gs. Notably, there was no significant difference between the 3000 Gs and 4000 Gs treatments, but capacity was significantly higher than that under the other treatments.

The ratio of 0-80 cm soil water storage and 0-160 cm soil water storage (ΔR) was significantly higher under the magnetized treatment than that under the unmagnetized treatment (Table 4). Under the same magnetization frequency, ΔR was higher under M2 than M1, and the ΔR values were in the order: 4000 Gs > 3000 Gs > 5000 Gs > 2000 Gs > 1000 Gs. Therefore, magnetized water irrigation increased the water holding capacity of the upper middle layer of the soil.

Table 4 Cumulative change in average soil water storage capacity in different soil layers under magnetized water irrigation treatment

Treatment	**Magnetization frequency**	**Magnetization intensity/Gs**	**Change of average soil water storage $\Delta C l$（mm）**			**Ratio of 0-80 cm soil water storage and 0-160 cm soil water storage (ΔR)**
			0-80 cm	0-120 cm	0-160 cm	
CK	0	0	56.99d	66.26d	149.08b	38.22%
M1G1（T1）	1	1000	62.20c	74.56c	151.91b	40.95%
M1G2（T2）		2000	63.31c	76.95c	151.34b	41.83%
M1G3（T3）		3000	79.35b	95.90a	154.71b	51.29%
M1G4（T4）		4000	79.53b	97.38a	154.11b	51.61%
M1G5（T5）		5000	64.33c	83.86b	152.08b	42.30%
M2G1（T6）	2	1000	66.62c	79.74c	153.25b	43.47%
M2G2（T7）		2000	69.91c	81.58bc	154.08b	45.37%
M2G3（T8）		3000	85.07a	100.62a	161.98a	52.52%
M2G4（T9）		4000	86.51a	97.49a	161.39a	53.60%
M2G5（T10）		5000	70.52b	88.69b	152.34b	46.29%

Note: irrigation time is July 31, 2021. The lower case letters within columns indicate significant differences at the 0.05 level.

3.3 Soil salinity

The distribution of salt in different soil layers during the growth of jujube is shown in Figure 7. The salt distribution under different treatments in the 0-160 cm soil layer was consistent, and the salt content showed the phenomenon of surface concentration. The soil salt content of the 0-60 cm soil layer showed a decreasing trend, and the soil salt content was concentrated in the 80 cm soil layer. The soil salt content of the 100-160 cm soil layer showed a gradually increasing trend, and the average salt content of the 100-160 cm soil layer was greater than the average salt content of the 0-60 cm soil layer. During the fruit expansion stage, water and salt moved to the 100-160 cm soil layer with the increase of irrigation water.

Under the same number of magnetization events, compared with the CK treatment, the soil salt content under magnetized water irrigation decreased significantly, and the average salt content of the soil under different magnetization intensities was in the order: 3000 Gs < 4000 Gs < 2000 Gs < 5000 Gs < 1000 Gs < CK. Compared with the CK treatment, the average soil salt content of under the 1000 Gs, 2000 Gs, 3000 Gs, 4000 Gs, and 5000 Gs treatments following M1 and M2 decreased by 15.0%, 22.8%, 32.8%, 26.3%, 21.3% and 19.0%, 26.8%, 33.7%, 29.3%, 29.0%, respectively. Following magnetization at 1000 Gs, 2000 Gs, 3000 Gs, 4000 Gs, and 5000 Gs, the average soil salt content under M2 decreased by 5.2%, 5.6%, 1.8%, 4.5%, and 3.3% compared with M1, respectively. When the magnetic intensity was 3000 Gs, the salt content of the 0-80 cm soil in the root layer of jujube was relatively low, and the desalting effect of two magnetization events was better than that of one magnetization event.

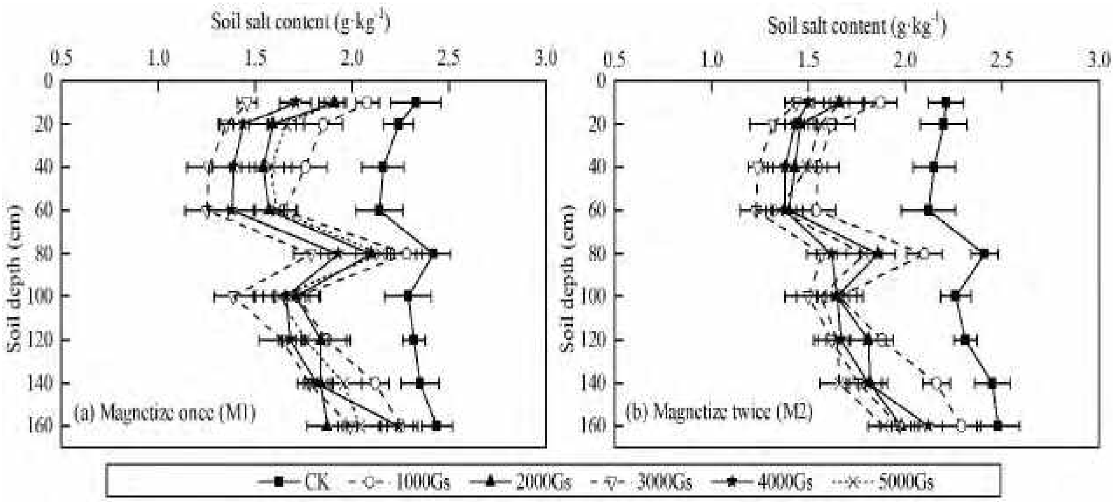

Figure 7. Vertical distribution of salinity content in jujube growth period under magnetized water irrigation

3.4 Effect of magnetized brackish water irrigation on the salt balance of jujube before and after its growth period

The change in soil salt storage in the 0-160 cm soil layer before and after the growth period of jujube under the magnetized brackish water irrigation is presented in Table 5. The 0-160 cm soil layer treated with magnetized brackish water showed salt accumulation. Under the same number of magnetization events, the change in salt storage for each treatment was in the order 3000 Gs < 4000 Gs < 5000 Gs < 2000 Gs < 1000 Gs < 0 s, and the change in salt storage in the M2 treatment was significantly lower than that in the M1 treatment. Under the M1 and M2 treatments, the salt accumulation rates following magnetization at 0 Gs, 1000 Gs, 2000 Gs, 3000 Gs, 4000 Gs, and 5000 Gs before and after the growth period of jujube were 39.37%, 22.44%, 18.69%, 9.96%, 16.42%, 16.05% and 16.35%, 9.58%, 4.96%, 8.27% and 12.59%, respectively. The soil salt accumulation rate following M2 and 3000 Gs treatments was the lowest, while that in the unmagnetized treatment was the highest.

Compared with the CK treatment, the change in soil salt storage before and after the growth period of jujube under treatments 1–10 (Table 5) decreased by 44.99%, 48.05%, 69.02%, 63.31%, 58.28%, 54.28%, 72.75%, 86.78%, 76.17% and 71.16%, respectively. Compared with the unmagnetized treatment, magnetized water irrigation significantly reduced the soil salt content.

Table 5 Changes to salt storage in the 0-160 cm soil layer before and after the growth period of jujube under magnetized brackish water irrigation

Treatment	Magnetization frequency (M)	Magnetization intensity（Gs）	Average initial salt storage of soil before irrigation (g)	Soil salt storage after harvest (g)	Change in salt storage (ΔS g^{-1})	Desalination rate (%)
M1G1（T1）	1	1000	4265.10	5222.10	-957.00	22.44
M1G2（T2）		2000	4836.21	5740.06	-903.85	18.69
M1G3（T3）		3000	5411.99	5950.90	-538.91	9.96
M1G4（T4）		4000	3887.56	4525.82	-638.26	16.42
M1G5（T5）		5000	4521.32	5247.18	-725.86	16.05
M2G1（T6）	2	1000	4864.26	5659.66	-795.40	16.35
M2G2（T7）		2000	4952.13	5426.31	-474.18	9.58
M2G3（T8）		3000	4652.89	4882.97	-230.08	4.96
M2G4（T9）		4000	5012.64	5427.26	-414.62	8.27
M2G5（T10）		5000	3987.46	4489.31	-501.85	12.59
CK	0	0	4419.58	6159.40	1738.82	39.37

3.5 Soil salt base ions

The Piper diagram shows the composition and evolution characteristics of main ions in the soil solution irrigated with different magnetized water treatments (Yang et al., 2020; Wang et al., 2019b; Liu et al., 2020); (a) the initial percentage ratio of soil salt ion groups under different treatments before magnetized water irrigation; (b) the percentage ratio of soil salt ion groups at the end of the growth period of jujube under different magnetized water irrigation treatments (Figure 8, b). Before magnetized water irrigation, the relative percentages of Na^+, Ca^{2+}+K^+, Cl^- and SO_4^{2-} were high in the initial soil ion composition. The relative percentage of the cation Na^+ was 40%-70%, and the relative percentages of anions Cl^- and SO_4^{2-} were 75%-95% (Figure 8a).

The percentages of the anion and cation groups in the soil solution changed significantly at the end of growth period after irrigation with magnetized water. The percentage of Ca^{2+}+K^+ and Mg^{2+} among the cations in the 0-100 cm soil solution increased, while the percentage of Na^+ decreased significantly. The relative percentages of Cl^- and SO_4^{2-} decreased significantly, while the relative percentages of CO_3^{2-} and HCO_3^- increased, indicating that the composition and proportion of soil salt base ions were changed by magnetized water irrigation, and the leaching effect of magnetized water irrigation on Na^+, Cl^-, and SO_4^{2-} was more obvious.

Under the same magnetization intensity, the leaching effect of twice magnetized water on the concentrations of Na^+, Cl^-, and SO_4^{2-} in soil was more significant than that of once magnetized water. Compared with the CK treatment, the relative percentage content of Na^+ and Cl^- in each treatment decreased by 24.67%~82.36%, and the relative percentage content of Na^+ and Cl^- decreased by 80.90% and 82.36%, respectively, under the M2 treatment at 3000 Gs. Cl^- and Na^+ are the main salt ions that cause soil salinization [3]. Magnetized water irrigation can leach more Na^+ and Cl^- out of the soil, thereby reducing the harm caused by soil salinization, which is of great significance to the improvement of saline soil.

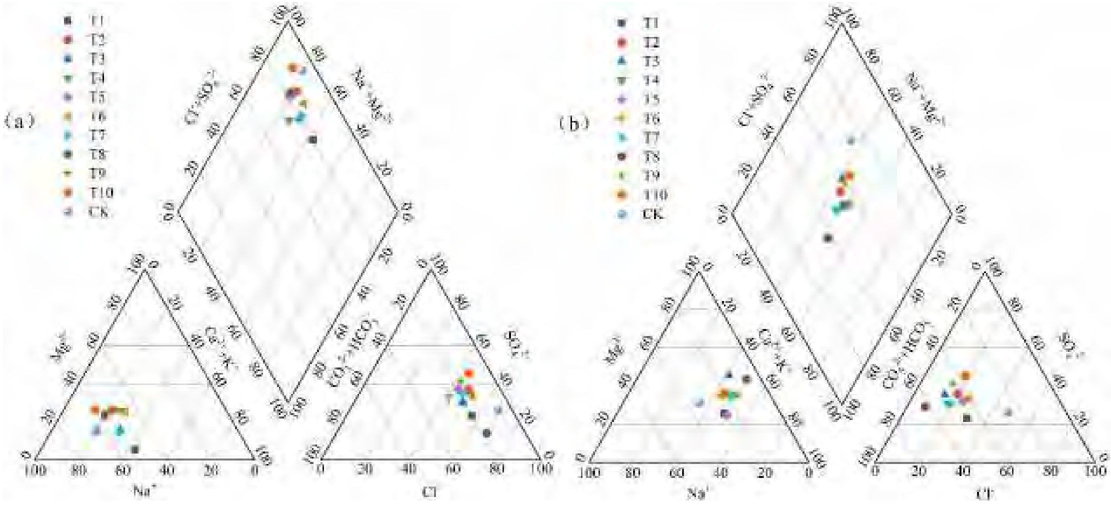

Figure 8. Piper diagram showing pre and post-irrigation characteristics under different magnetization treatments.

3.6 Soil total carbon and nitrogen content

The total C content of 0~100 cm soil irrigated with magnetized water was 59.02~84.96 mg · g^{-1}, and the total N content of the soil was 2.19-4.86 mg · g^{-1}. The total C and N contents of soil irrigated with unmagnetized water were 52.01 mg · g^{-1} and 1.96 mg · g^{-1}, respectively (Figure 9). Compared with the unmagnetized water irrigation treatment, the total C content when magnetized water was used for irrigation increased by 13.48%-63.35%, and the total N content increased by 11.73%-147.96%. Under magnetization intensities of 1000 Gs, 2000 Gs, 3000 Gs, 4000 Gs, and 5000 Gs, the total C content of soil under the M2 treatment increased by 12.03%, 8.92%, 6.9%, 11.42%, and 9.39%, and the total N content increased by 28.02%, 57.53%, 11.88%, 26.23%, and 10.91%, respectively, compared with M1. Magnetization intensity had a significant effect on increasing the soil C and N contents, which first increased and then increased with the magnetization intensity. Under M1 and M2, when the magnetization intensity was 3000 Gs and 4000 Gs, the soil total C and N content was relatively high, and there was no significant difference between the 3000 Gs and 4000 Gs treatments.

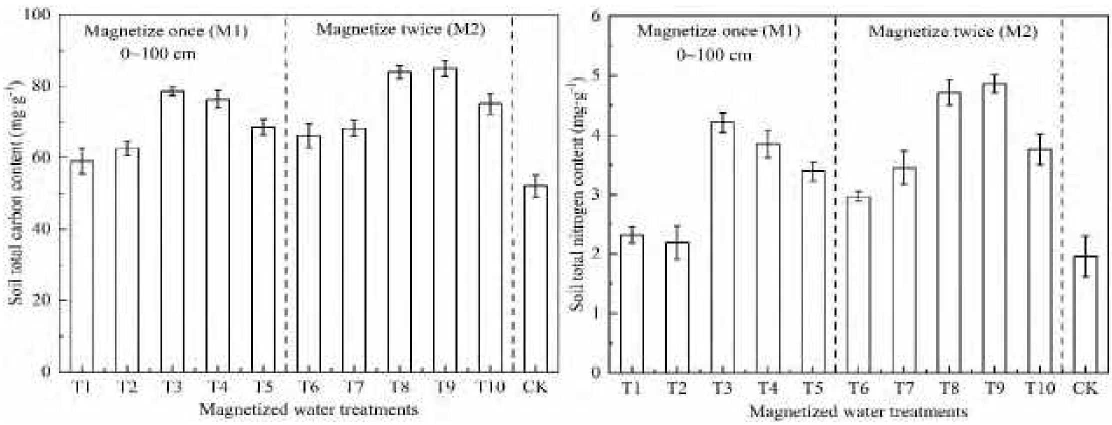

Figure 9. Effects of magnetized water irrigation treatment on total carbon and total nitrogen content in the soil root layer of jujube

4. Discussion

The results revealed that drip irrigation with magnetically-treated brackish water could make the water molecules enter the finer soil particle space and improve the soil water holding capacity. After being treated at different magnetization intensities, the average soil water content was greater than that under the unmagnetized treatment

(Figure 6), which was consistent with the results obtained by Peng et al., who found that magnetized water drip irrigation enhances soil water retention and effectively improves soil water content (Peng et al., 2019). The properties and functions of the irrigation water following magnetization changed significantly, which promoted the infiltration of water through the soil surface (Otsuka et al., 2006). Cai et al. (2009) concluded that as the surface tension of brackish water decreases, the viscosity increases, and the activation energy of water molecules increases after being magnetized at a constant velocity in the magnetic field. In addition, water molecules form new hydrogen bonds during the magnetic treatment process. Magnetized water irrigation increases the water content of the upper soil layer and reduces water infiltration to the deep soil (Wang et al., 2020), which is consistent with our findings. In another study, the magnetization of brackish water at low concentration penetrated the upper soil profile more slowly, thus reducing deep seepage and retaining more water in the upper layers (Guo et al., 2011). Our results also confirm this conclusion. In our study, after being magnetically treated at different intensities, the average water content of soil increased by 9.8%~38.6%. The reason for this increase was that the original structure of the water molecular group changes (Chang et al., 2006; Yang et al., 2003) after magnetization treatment and the osmotic pressure increases (Ding et al., 2011), which causes more water to enter soil pores, thus, increasing soil water content, indicating that magnetized water irrigation can increase the soil water holding capacity.

According to the soil salt distribution and leaching effect under magnetic brackish water drip irrigation, magnetic water irrigation reduced the soil salt content of the 0-80 cm soil layer, which corresponded to soil layer around the roots of the jujube trees. Magnetized water irrigation enhanced the leaching of soil salt and reduced the soil salt accumulation rate. The composition and proportion of soil salt base ions were changed by magnetized water irrigation, and the leaching effect of magnetized water irrigation on Na^+, Cl^-, and SO_4^{2-} was more obvious. The salt leaching effect was most significant under the M2 treatment at 3000 Gs. These findings were consistent with previous studies. Magnetized water irrigation can promote soil desalination, significantly reduces the contents of exchangeable and total sodium in soil and is conducive to improving the soil salinization environment (Wang et al., 2018). Magnetized water irrigation can promote the downward movement of soil salt and enhance the leaching of soil salt ions Cl^- and Na^+, but has little impact on HCO_3^-, and the effect of secondary magnetization is greater than that of primary magnetization (Zhang et al., 2014). Mostafazaden et al. (2012) showed that magnetized water irrigation not only leached Cl^- significantly, but leached HCO_3^- and Na^+ more than unmagnetized water. The contents of Cl^- and SO_4^{2-} in the 0~60 cm soil layer decreased significantly under mulched drip irrigation with magnetized water (Bu et al., 2010). Magnetized water improves the solubility of various minerals (Lin et al., 1999). The activity of magnetized water is enhanced, and the ability to dissolve salt is improved. The salt leaching efficiency increases first and then decreases with magnetization (Wang et al., 2020). This finding was consistent with our study. In our study, magnetized water irrigation enhanced the leaching of soil salt and reduced the soil salt accumulation rate. The reason may be that the structure of the water molecule changes after magnetization, the viscosity and association degree of water decreases, the solubility of soluble salt increases, and the salt leaches to the deep soil (Li et al., 2017).

Compared with the unmagnetized treatment, the total C content increased by 13.48%-63.35%, and the total N content increased by 11.73%-147.96% when irrigated with magnetically-treated brackish water, and showed a trend of first increasing and then decreasing with magnetization. In general, the use of magnetized water irrigation in saline alkali land can increase the leaching effect of soil salt, reduce the percentage contents of Na^+ and Cl^- in soil, improve the soil microenvironment, reduce the harm caused by salt to crops, and help to improve the physiological activity of crop roots. These findings provide theoretical support for the application of magnetized water irrigation technology in agriculture.

5. Conclusions

Soil salinization is an important factor affecting agricultural development in arid oasis regions. A field experiment was carried out to study the mechanism behind the influence of magnetized brackish water drip irrigation on soil water and salt transport in a typical dryland area of southern Xinjiang, China. The results revealed that drip irrigation with magnetically-treated brackish water could reduce the water transport rate and improve the soil water holding capacity. Magnetized water irrigation enhanced the leaching of soil salt and reduced the soil salt accumulation rate. The lowest soil salt accumulation rate was 4.96% under treatment with water twice magnetized at 3000 Gs. The composition and proportion of soil salt base ions were changed by magnetized water irrigation, and the leaching effect of magnetized water irrigation on Na^+, Cl^- and SO_4^{2-} was more obvious. Moreover, the effect of the twice magnetized water was greater than that of the once magnetized water. The relative percentage contents of Na^+ and Cl^- decreased the most, to 80.90% and 82.36%, respectively, under treatment with water twice magnetized at 3000 Gs. Magnetization intensity had a significant increasing effect on soil C and N contents, which first increased and then decreased with the magnetization intensity. Magnetized water irrigation can reduce the risk of soil salinization, reduce the salt stress of crops in arid areas, and provide a theoretical basis for the use of magnetized water technology to alleviate the shortage of freshwater resources and safely use brackish water.

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EFFECTS OF SOIL TEXTURE ON SOIL LEACHING AND COTTON (GOSSYPIUM HIRSUTUM L.) GROWTH UNDER COMBINED IRRIGATION AND DRAINAGE

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ABSTRACT

To further explore the effects of different soil textures on soil leaching and cotton (Gossypium hirsutum L.) growth using a combined irrigation and drainage technique and provide a theoretical basis for the improvement of saline alkali land in Xinjiang, we used a test pit experiment to test soil moisture, salinity, soil pH, permeability, cotton agronomic characteristics, cotton yield and quality, and water use efficiency in three soil textures (clay, loam, sand soil) under the combined irrigation and drainage (T1) and conventional drip irrigation (T2). We measured the soil moisture content in different soil layers of clay, loam and sandy soil under the T1 and T2 treatments. Clay and loam had better water retention than sandy soil, and the soil moisture under the combined irrigation and drainage treatment was slightly higher than that under conventional drip irrigation. Under T1, the average salt content and pH value in the 0–60 cm soil layer of clay, loam and sandy soil decreased by 14.09%, 14.21% and 12.35%, and 5.02%, 5.85% and 3.27%, respectively, compared with T2. Therefore, T2 reduced the salt content and pH value of shallow soil. Under T1 and T2, the relative permeability coefficient (K/K0) values in different soil textures at different growth stages of cotton were ranked as follows: sandy soil > loam > clay. Under T1, the K/K0 values for different soil textures at different growth stages of cotton were >1; therefore, T1 improved soil permeability. The yield and water use efficiency of seed cotton under T1 and T2 in different soil textures were ranked as follows: loam> clay> sand, and there were significant differences between the different treatments. In loam, the cotton yield and water use efficiency of the combined irrigation and drainage treatment were 6.37% and 13.70% higher than those for conventional drip irrigation treatment, respectively. By combining irrigation and drainage to adjust the soil moisture, salt, pH value and soil permeability of different soil textures, the root growth environment of crops can effectively be im-proved, which is of great significance to improving the utilization efficiency of water and fertilizer and promoting the growth of cotton.

Keywords: combined irrigation and drainage; soil texture; soil moisture; soil salinity; Soil pH; permeability; cotton yield; WUE

1. Introduction

Due to increasing requirements for agricultural development, a lack of resources and associated environmental problems has become increasingly prominent. China is a large agricultural country with a big population base and a shortage of resources. The scarcity of water resources and secondary salinization of soil have become important factors restricting agricultural development (Wan et al., 2016). Xinjiang is located in an arid area of Northwest China and is the largest cotton (Gossypium hirsutum L.) growing area in China. Oasis farmland in Xinjiang is essential to the livelihoods of many members of the population and is critical to social and economic development in this part of the country (Zhang et al., 2009). The area experiences low levels of rainfall, high levels of evaporation and severe soil salinization. To alleviate water shortages and improve water use efficiency in Xinjiang, the area has aggressively been developing the use of drip irrigation under plastic film since 1996. The application of drip irrigation under plastic film improves the efficiency of water utilization. The application of drip irrigation technology has resulted in the reduction of field channel systems, which, coupled with the large-scale planting of crops and imperfect field drainage systems, have resulted in rising groundwater levels and the migration of soil salt in the water to the surface soil. However, due to a lack of field drainage infrastructure, the secondary salinization of oasis farmland (agriculture in arid and desert areas made possible through irrigation) has introduced new challenges. Over a third of the cultivated land in Xinjiang is endangered by different degrees of salinization and secondary salinization (Wang et al., 2019a). With the rapid development and increased use of drip–irrigation under film, secondary salinization of farmland has accelerated, therefore efforts to protect the soil and ecology of the area have been strengthened. Accordingly, engineering technologies for modernization (water consumption monitoring technologies, pipeline water delivery and distribution technologies, scheduling and

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control technologies of water use, on-farm irrigation technologies, etc.) to improve field water conservancy, field management, saline alkali soil, field drainage and salt discharge efficiency are being implemented so as to raise the yield and quality of crops and ensure the sustainable development of agriculture in the area. The combination of irrigation and drainage is a new modern technology of irrigation system, which combines drip irrigation technology with subsurface drainage technology.

Soil is an important part of the agricultural ecological environment. Protecting soils and improving the ecological structure of the area guarantees the sustainable development of oasis agriculture (Zhao et al., 2019). Texture is a physical property of soil and refers to the different sizes of the mineral particles (Wang et al., 2019b); it is an important index that reflects the potential productivity of the soil. Soil texture is significantly related to soil moisture, nutrient content, pH, salt content and aeration as well as farming difficulty (Arora et al., 2011). The measures of aeration, fertility and thermal characteristics of soils with different textures vary greatly (Katerji et al., 2009). The moisture content, temperature, pH and salt distribution in different textures of soil affect the physiological indexes of crop growth, including the retention capacity for water and fertilizer and the water use efficiency (Zhang et al., 2008).

Previous reports have described the effects of different soil textures on soil leaching and crop growth. For example, Li Chaohai et al. (2007) investigated the biological activity of rhizospheres in different soil textures and concluded that the biological activity in the maize rhizosphere is affected by the growth of the crop and the soil texture. Coarse textured soils led to the least amount of available water and an increased soil drought index (Wang et al., 2019c). Moreover, soil pH affects the forms, availability, migration and transformation of various elements in soil (Zheng et al., 2014). In studying the effect of texture on soil physical properties, previous researchers concluded that when the sand content of soil is 30–70%, the addition of organic matter can significantly improve the soil water holding capacity (Li et al., 2001). There is a good quantitative relationship between the thermal properties of soils with different textures and soil water suction (Luo et al., 2010). Previous studies on the effects of soil texture on cotton growth and yield have been carried out on crops grown using a traditional drip irrigation under film method.

The dynamics of cotton nutrient accumulation and fertilizer utilization efficiency in sandy and heavy loam, while the effects of different soil textures on cotton yield and boll distribution were also studied, it was concluded that the boll setting capacity in loam soil was greater than that in clay or sandy soil (Luo et al., 2009; Dou et al., 2020). Salt transport when using drip irrigation under film in cotton fields was also studied with respect to different soil textures. It was subsequently pointed out that flood irrigation should be carried out regularly and alkali drainage channels should be restored (Wang et al., 2019a). In recent years, many scholars have recognized the importance of field drainage (Tahir et al., 2021; Wang et al., 2021).

Research shows that the construction of drainage channels, including shaft drainage and concealed pipe drainage, can improve the drainage efficiency of farmland and have significant effects on inhibiting soil salinity and promoting crop growth (Zhang et al., 2018; Wang et al., 2020; Li et al., 2016). When using concealed pipe drainage, the soil salt status changes from “high salt heterogeneity” to “low salt homogeneity”, which effectively reduces the amount of soil salt ions (Zhang et al., 2008). Zhang et al. (2018) previously carried out a numerical simulation and analysis of combining drip irrigation under plastic film and salt drainage through concealed pipes and was able to simulate the movement of water and salt during the process of salt drainage. The coordinated regulation of flood irrigation, leaching and concealed pipe drainage has achieved remarkable results in improving saline alkali soil. Reasonable irrigation and concealed pipe layout spacing can improve leaching efficiency (Xin et al., 2017). However, there have been few studies on the effects of soil texture on soil leaching and cotton growth when irrigation and drainage are linked.

Irrigation is very important to the sustainable development of agriculture in Xinjiang, but the construction and development of field drainage projects and advances in drainage and salt removal efficiency also play very important roles in improving the farmland soil environment and crop growth (Fabio et al., 2015). With the increase in the area of farmland under plastic film undergoing drip irrigation and the acceleration of farmland secondary salinization, it is important to explore the water and salt distribution in different textures of soil and crop growth responses under combined irrigation and drainage in order to popularize and apply this technology.

It is critical to explore the impact of drip irrigation under plastic film combined with concealed pipe drainage on soil leaching and cotton growth in soils with different textures. However, there are few previous studies on the effects of combined irrigation and drainage in different soil textures on soil leaching and crop growth. The purpose of this study was to determine the effects of different soil textures on soil leaching and cotton growth under combined irrigation and drainage so as to provide new ideas for promoting agricultural water saving and improving saline alkali land. Our research group hypothesized that combined irrigation and drainage technology can improve the growth environment for cotton roots, reduce soil salt and improve cotton yield and quality compared with traditional drip irrigation under plastic film. Therefore, it is essential to study the effects of different soil textures on soil leaching and cotton growth using combined irrigation and drainage technology to provide information about the application of this method in soils with different soil textures.

2. Materials and Methods

2.1 Experimental Site

The experiment was conducted at the Key Laboratory of Modern Water-Saving Irrigation of the Xinjiang Production and Construction Corps (85°59′E, 44°19′N, altitude 412 m) from April to November 2018 at Shihezi University in Xinjiang, China (Figure 1). The region experiences a typical arid continental climate, with an average annual rainfall of 210 mm, an average annual evaporation of 1600 mm, air temperature of 7.2°C, sunshine duration of 2,865 h and frost-free period lasting 171 days (Cao et al., 2017). The active accumulated temperature above 10°C and 15°C were 3463°C and 2960°C, respectively. Changes in precipitation, reference crop evapotranspiration (ET_0, the ET_0 is calculated by Penman-Monteith (Yin et al., 2008)) and maximum atmospheric temperature in the cotton-growing season (from April to November) in 2018 is presented in Figure 2. A total of 153.8 mm of rain fell during the cotton-growing season. Air temperature, precipitation, wind speed, humidity and other meteorological data were recorded by an automatic weather station (TRM-ZS2 type, Jinzhou Sunshine Meteorological Technology Co., Ltd., Jinzhou, China). The weather station was set up at our experiment site.

The experimental area comprised 0.0216 ha. The regional ground-water table remained at a depth of 8 m. The cotton cultivar 'Nong feng 133' was used, which is suitable for dense planting, good ventilation, light transmission among populations, early maturity and high yield. This cultivar is also suitable for machine planting and harvesting. The soil particle composition and physical indexes (e.g., dry bulk density and nutrient content) of the 0–100 cm soil layers in the test area are shown in Table 1.

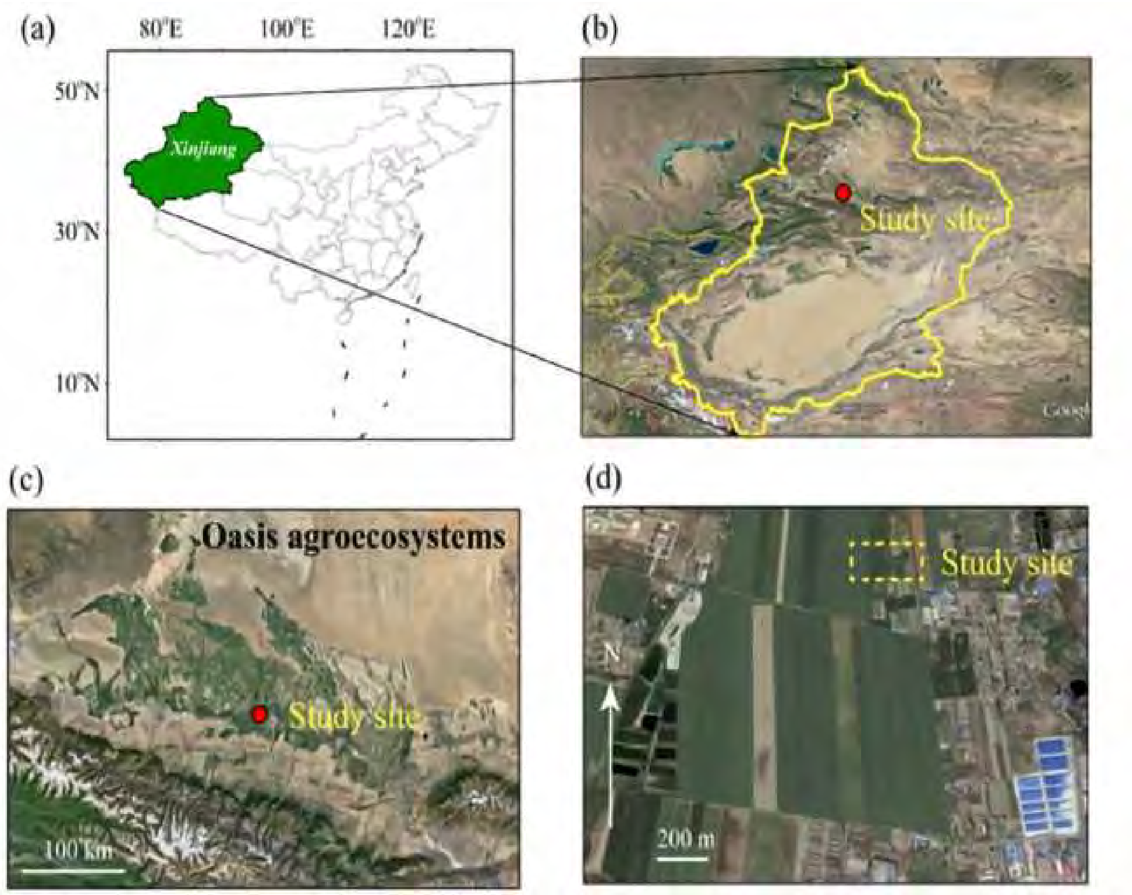

Figure 1. Maps and imagery of the study site. Xinjiang is located in the northwest of China (a) and is characterized by an extremely arid desert climate (b). Large agricultural irrigation demand is required for the oasis agroecosystems in Xinjiang (c). Field experiments were conducted at the Key Laboratory of Modern Water Saving Irrigation of the Xinjiang Production and Construction Corps (85°59′47″E, 44°19′29″N) in Shihezi City, Xinjiang (d).

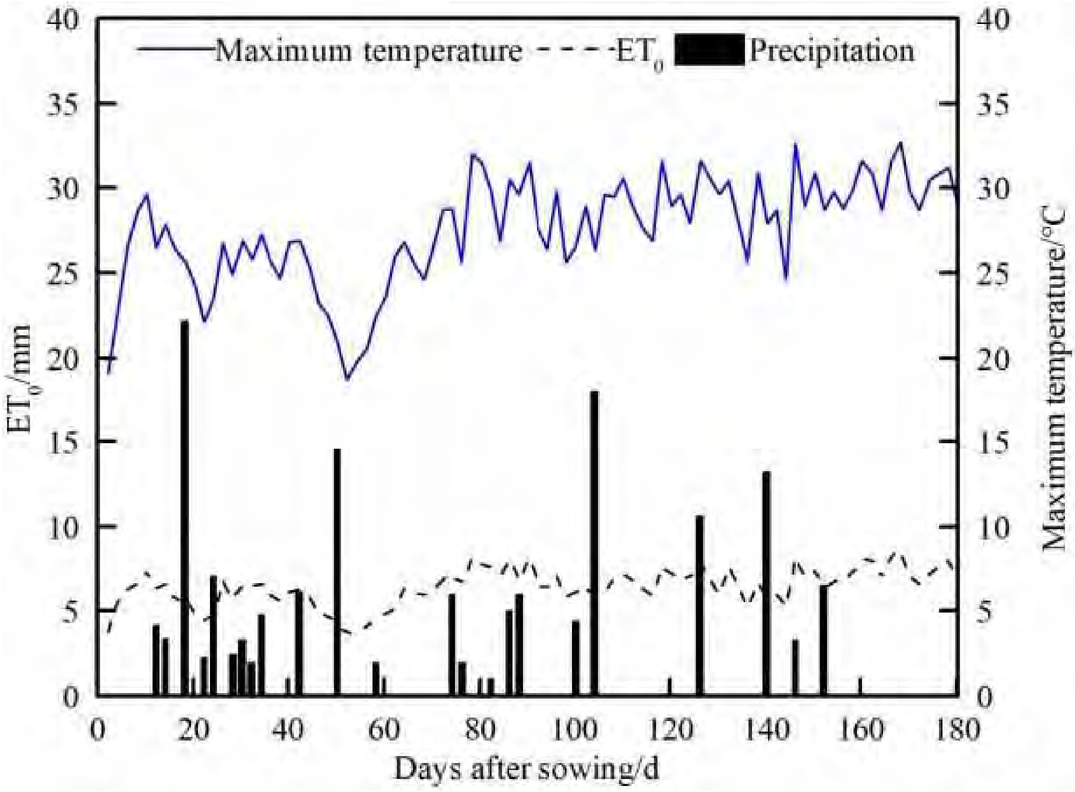

Figure 2. T-max (the maximum air temperature, indicated by the curves), daily precipitation (indicated by the bars) and ET_0 (reference crop evapotranspiration, indicated by the dashed curve) during the cotton growing season at the experimental site in 2018.

Table 1. Composition and physical indexes of soil particles in the experimental area.

Soil Texture	Soil Particle Composition/%			Total Nitrogen (g/kg)	Available Nitrogen (mg/kg)	Available Phosphorus (mg/kg)	Available Potassium (mg/kg)	Organic Matter (g/kg)	Average Bulk Density of 0–100 cm Soil
	<0.002 mm	0.002–0.02 mm	0.02–2 mm						
Clay	28	40	32	0.78	100.43	9.15	188.70	10.45	1.35
Loam	12	43	45	0.56	77.45	16.45	417.50	9.55	1.55
Sand	9	14	77	0.34	59.56	8.42	102	4.52	1.72

2.2 Experimental Site

A split-plot experimental design was adopted, whereby the plots did or did not contain concealed pipe drainage. The main plots included T1 (cotton grown under drip irrigation under plastic film combined with concealed pipe drainage) and T2 (cotton grown under conventional drip irrigation under plastic film). Soils with different textures were applied to the subplots, including clay, loam and sandy soil. Each subplot was about 12 m^2 (3 m × 4 m), and three replications were conducted in each subplot, with a total of 18 plots. The cotton planting model with one film, three drip tapes and six rows (Figure 3) was adopted for each subplot. We used a machine-harvested cotton planting pattern (10-cm plant distance, 66 cm + 10 cm of wide-narrow rows, and a planting density of 260,000 plants ha^{-1}), and a total of 312 plants were included in each plot. The soil particle composition and physical indexes in the test areas are shown in Table 1.

The cotton was sown using the "dry sowing and wet out" method (the water storage and salt drainage technology for drip irrigation under plastic film). The cotton was planted on 22 April 2018. During the growth period, the drip irrigation method under the film was used to provide the necessary water and nutrients for cotton growth. The drip irrigation capillary was a single-wing labyrinth thin-walled drip tape. The emitter flow rate was 2.6 L h^{-1}. The distance between the drippers was 30 cm, and the thickness of the plastic film was (0.008 ± 0.0003) mm. The water supply system in the study area was pressurized mainly by a water pump, and the pressure gauge and regulating valve were installed at the head of the system. The amount of irrigation, irrigation dates and frequencies, and fertigation frequencies for the T1 and T2 treatments were the same throughout the experiment. The cotton was irrigated 13 times during the whole growth period. In total, 450 mm of irrigation were applied; N fertilizer was applied at 225 kg ha^{-1} and P fertilizer at 140 kg ha^{-1} during the whole growth period. Irrigation was carried out by drip irrigation under the mulch. The irrigation interval was 7–10 days: four times during the seedling stage, four times during the flowering period, three times during the bolling period and twice during the mature stage. The fertilizer was dissolved in the water used for irrigation. The details of irrigation and fertilization management during the cotton growth period are shown in Table 2. For each subplot under the T1 treatment, two concealed pipes were buried in each test pit. The concealed pipes were buried in the middle of the wide row of cotton, with a spacing of 1 m, and buried at a depth of 60 cm at a pre-designed slope of 2 %. PVC double walled corrugated pipe 100 mm in diameter was used for the drainage pipe, and eight water inlets were evenly distributed around its circumference. The buried concealed pipe was wrapped with non-woven fabric to prevent soil particles from entering it. The cotton planting mode is shown in Figure 3.

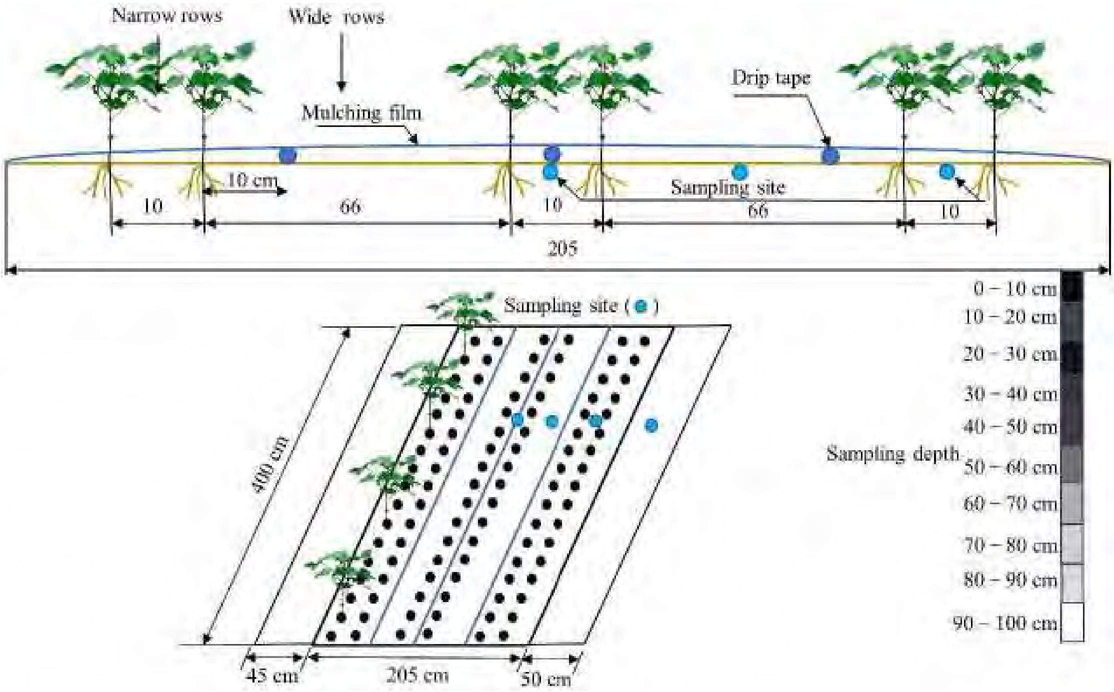

Figure 3. Schematic diagram of cotton planting pattern (unit: cm).

Table 2. Irrigation schedule during the cotton growing season in 2018.

Growth Stage *	Irrigation Date	Irrigation Quota (mm)
Seedling	24 April 2018	20
	9 June 2018	25
	16 June 2018	25
	23 June 2018	25
Flowering	1 July 2018	50
	9 July 2018	50
	16 July 2018	50
	23 July,2018	50

Growth Stage *	Irrigation Date	Irrigation Quota (mm)
Bolling	30 July 2018	35
	6 August 2018	35
	13 August 2018	35
Maturity	20 August 2018	25
	27 August 2018	25
Total irrigation amount (mm)		450

* Seedling stage indicates the period from emergence to budding of cotton; flowering indicates the beginning of flowering; bolling indicates boll development; and maturity indicates that over 90% of bolls are open. Definitions of cotton phonological stages are from Munger et al. (Munger et al., 1998).

2.3 Sampling and Field Measurements

2.3.1 Soil Water Content

The soil moisture was measured to a depth of 100 cm at 10 cm intervals during different cotton growth periods. The sampling points were located between the wide and narrow rows of cotton and the bare ground outside the film (Figure 3). Soil was removed directly through the film by drilling a hole, and the hole was backfilled with fine soil. Soil samples were collected using a stainless-steel ring knife (100 cm^3). Three replicate soil samples were taken at each depth. These soil samples were oven-dried to a constant weight to calculate the gravimetric soil moisture. The volumetric soil moisture content was calculated based on the measured gravimetric soil moisture and soil bulk density. Soil water storage was calculated to a depth of 0–100 cm.

2.3.2 Soil Salinity

Soil samples were collected from the wide and narrow rows of cotton under plastic film at different stages of plant growth. To measure soil salinity, the oven-dried soil samples were pulverized and passed through a 1 mm sieve. Then, 20 g of soil powder were taken from each sample and mixed at a ratio of 1:5 with water. After being evenly shaken, the mixture was set aside for 2 h. The electrical conductivities ($EC_{1:5}$) of the mixtures were measured using a portable electrical conductivity meter (DDS11-A, manufactured by Shanghai Leichi, China). The absolute change (ΔS) and relative change (R) in soil salinity were calculated as:

$$\Delta S = EC_{1:5}{}' - EC_{1:5} \tag{1}$$

$$R = \frac{\Delta S}{EC_{1:5}} \times 100\% \tag{2}$$

where $EC_{1:5}$ and $EC_{1:5}'$ (ds m^{-1}) represent soil salinity before sowing and after harvest, respectively.

2.3.3 Soil Permeability Coefficient

The outdoor double ring infiltration method was used to determine the soil permeability coefficient. The K was calculated as:

$$K \text{ (soil permeability coefficient)} = QL/F\,(H + Z + L) \tag{3}$$

where Q represents the stable infiltration water volume (cm^3/min), F represents the water seepage area of the inner ring of the test pit (cm^2), Z represents the water thick-ness in the inner ring of the test pit (cm), H represents the capillary pressure (generally equal to half of the capillary rise in the soil) (cm), L represents the penetration depth of water (determined by excavation after test) (cm).

The dimensionless parameter relative permeability coefficient was used to characterize the change in soil permeability. The relative permeability coefficient is the ratio of the measured (0~100 cm) average permeability coefficient K and the initial average permeability coefficient K0 of different soil textures treated with T1 and T2. The relative permeability coefficient was used to reflect the change in the soil permeability coefficient. When K/K0 is greater than 1, the soil permeability coefficient increases, while a smaller K/K0 indicates a decrease in permeability.

2.3.4 Soil Ph

To measure soil pH, the oven-dried soil samples were pulverized and passed through a 1 mm sieve. Then, 20 g of soil powder were taken from each sample and mixed at a ratio of 1:1 with water. The mixture was stirred three times at intervals of about 1 h. After stirring, the pH of the mixtures was measured using a pH meter.

2.3.5 Aboveground Dry Matter, Cotton Plant Stem, Plant Height, and Leaf Area

Five cotton plants from each test pit were selected at the cotton seedling stage (25 May), bud stage (25 June), flower and boll stage (25 July) and boll opening stage (September 1). The plant samples were dried to a constant weight to measure the biomass. Moreover, the date the plants entered each phenological stage (e.g., emergence, squaring, flowering, boll opening, and maturity) was recorded for all plots. The definition of each phenological stage was adopted from Munger et al. (Munger et al., 1998). Five representative cotton plants were selected from each plot at the emergence stage. The plant height, leaf length, and leaf width were measured every 10–15 days from the beginning of the emergence stage using a tape measure with an accuracy of 1 mm. The leaf area was measured using an empirical coefficient formula (0.75 × leaf length × leaf width) (Wang et al., 2017) and a handheld leaf area tester (Yaxin-1241 type, Beijing Yaxin Liyi Technology Co., Ltd., Beijing, China). Then, the average value was used for analysis.

2.3.6 Cotton Yield and Water Use Efficiency

Cotton yield was determined by hand harvesting in the crop following each treatment and calculating the yield per unit area (kg ha^{-1}). The water use efficiency (WUE, kg ha^{-1} mm^{-1}) was calculated as the ratio between the annual cotton yield (Y) and evapotranspiration (ET) over the growing season in each year (Hussain et al., 1998). Given the limited influence of groundwater on soil water and the lack of surface runoff at the experimental site, the ET could be calculated as:

$$ET = P_0 + I - D + \Delta SWS \quad (4)$$

$$WUE = \frac{\mathrm{Y}}{\mathrm{ET}} \quad (5)$$

where, P0 represents rainfall, I represents irrigation, D represents deep percolation (the amount of concealed pipe drainage) and ΔSWS represents the difference in soil water storage in the 0–100 cm depth of soil between sowing and harvest. Y is the annual cotton yield (kg ha^{-1}).

2.3.7 Cotton Fiber Quality

Representative points within an area of 4 m2 were selected in each test pit prior to harvesting to determine the boll weight and lint percentage. A sub-sample of lint was sent to the Supervision, Inspection and Test Center of Cotton Quality, Ministry of Agriculture and Rural Affairs, Anyang City, Henan Province, China to examine the fiber quality using a high-volume instrument (HVI) (Wang et al., 2019d).

2.4 Statistics and Analysis

The experimental data were graphed and processed using SPSS 20.0 and Origin 9.0. The SAS package (SAS Institute Inc., Cary, NC, USA) was used to conduct the analysis of variance (ANOVA). Differences were considered statistically significant when $p \leq 0.05$.

3. Results

3.1 Soil Water Content

The changes in the moisture content of different soil layers under the T1 and T2 treatments were measured after irrigation at the flowering and bolling stage (July 15) (Figure 4). Under T1 and T2 treatments, the soil moisture levels in clay and loam in different layers were significantly higher than those in sandy soil, and clay and loam showed better water retention than sandy soil. Compared with clay, the distribution of water within various layers loam and sandy soil changed regularly. Under combined irrigation and drainage (T1), the soil moisture content of the 0–40 cm soil layer in loam and sandy soil decreased gradually, that of the 40–60 cm layer increased, while that of the 60–100 cm layer showed little change. Under the conventional drip irrigation under plastic film treatment (T2), the soil moisture content of the 0–60 cm soil layer in loam and sandy soil decreased gradually, while that of the 60~100 cm soil layer increased gradually. In the T1 and T2 treatments, the soil moisture content of each layer in clay exhibited fluctuating changes.

Under the T1 and T2 treatments, the average water content of clay, loam and sandy soil was 15.97%, 15.36% and 6.41%, and 15.75%, 14.74% and 6.13%, respectively, in the 0–60 cm soil layer, and 16.45%, 16.04% and 5.89%, and 16.06%, 15.91% and 5.67%, respectively, in the 0–100 cm soil layer. Under the same treatment, the soil moisture content of the 0–60 cm layer and 0–100 cm layer in clay was the highest. The soil moisture content of the 0–60 cm layer and 0–100 cm layer in loam was slightly lower than that in clay, but the water distribution in loam was more conducive to cotton root absorption. The soil water content of the same soil textures for T1 was slightly higher than that for T2. The average moisture in the 0–60 cm layer of clay, loam and sandy soil under T2 was 92.37%, 97.96% and 95.63% of that in T1, respectively.

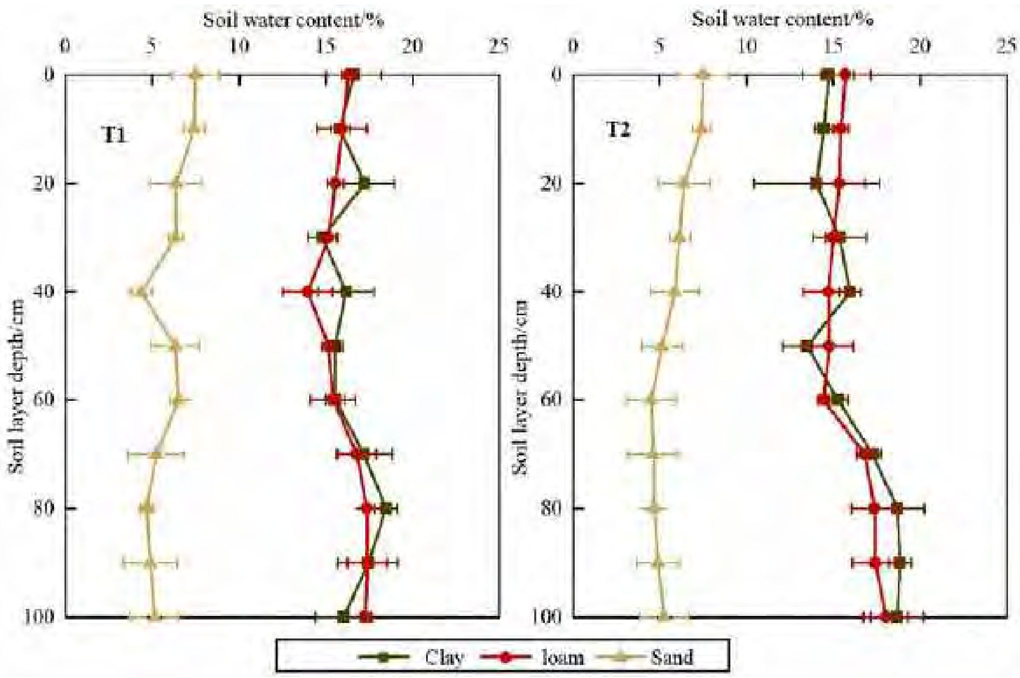

Figure 4. Distribution of moisture in three soil textures at different depths.

3.2 Soil Salinity

Under plastic film drip irrigation combined with concealed pipe drainage (T1), the salt content of the loam and sandy soil in the 0–60 cm soil layer showed a gradually decreasing trend, and the salt content of clay in the 0–60 cm layer also showed a decreasing trend except at 40 cm. The salt content in the 60–100 cm soil layer of different soil textures showed a gradual increase with depth (Figure 5). The T1 treatment was shown to reduce the salt content of shallow soils with different textures. The salt content in the 0–60 cm layer of loam under the T2 treatment gradually increased, while that in the 60–100 cm layer gradually decreased; the salt migrated to the layer of soil at 60 cm with water. The salt content in the 0–60 cm layer of the sandy soil decreased, while that in the 60–100 cm layer increased gradually with depth. Due to the dense structure of clay and a high content of small particles, it retained water well and irrigation water infiltrated slowly. Moreover, with water absorption, clay particles expanded during dripping irrigation, which hindered capillary water movement. There was a significant capillary effect between clay particles and slow permeability, so the distribution of the soil salt content in different soil layers fluctuated and had no obvious structure.

Following analyses of the 0–60 cm layer of soils with different textures under the T1 and T2 treatments, the average salt contents in clay, loam and sandy soil were 1.89 and 1.63 ds/m, 1.42 and 2.20 ds/m, and 1.90 and 1.62 ds/m, respectively. Compared with the T2 experiment, the average salt contents in 0–60 cm soil layer of clay, loam and sandy soil treated with T1 decreased by 14.09%, 14.21% and 12.35%, respectively. The cotton roots were mainly distributed in the 0–60 cm soil layer and we found that the linked irrigation and drainage treatment significantly reduced the salt content of the shallow soil.

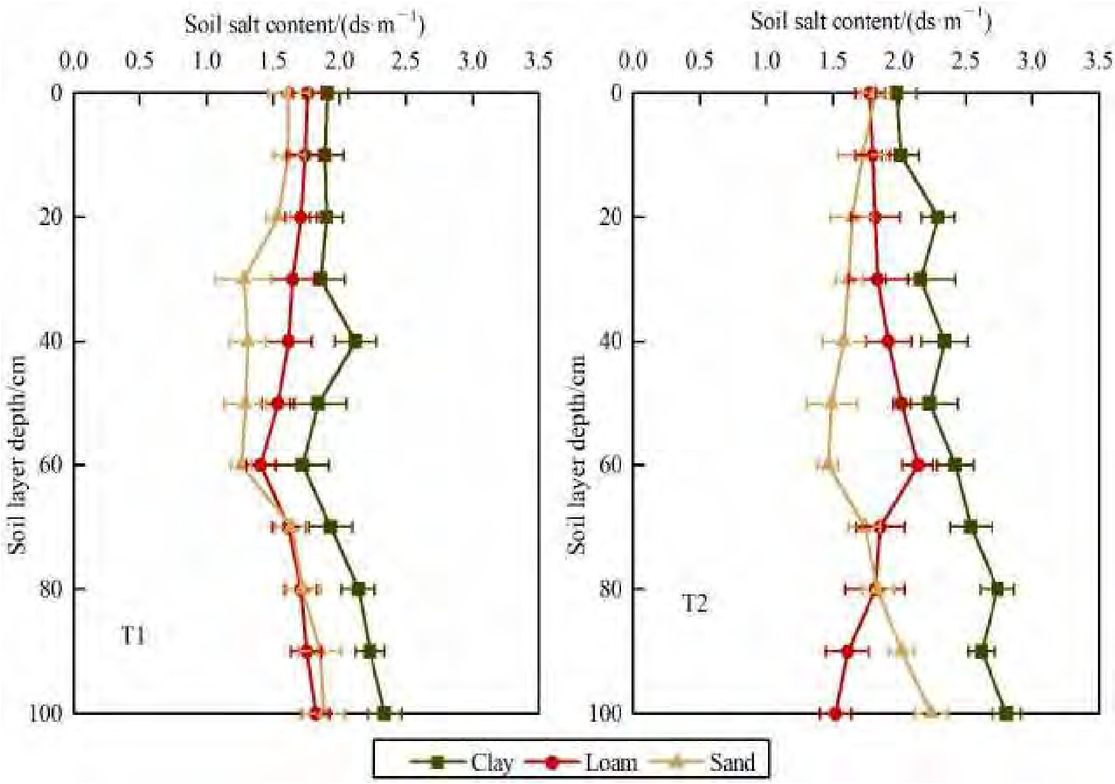

Figure 5. Distribution of salt in various layers of soil under two different treatments.

3.3 Soil Permeability Coefficient

The soil permeability coefficient is one of the main physical parameters used to determine soil permeability. Figure 6 shows the change in the relative permeability coefficient (K/K0) with cotton growth. A K/K0 value > 1 indicates that the soil permeability coefficient has increased. The smaller the K/K0 value, the greater the decrease in permeability. Under T1 and T2 treatments, the K/K0 values of different soil textures at different cotton growth stages were ranked as follows: sandy soil > loam > clay. The relative permeability coefficient of loam and sandy soil increased first and then decreased with the cotton growth stage. The maximum value was obtained at the flowering and bolling stage. The relative permeability coefficient of clay increased slightly, but the increment was lower than that in loam and sandy soil (Figure 6). The K/K0 values of different soil textures at different cotton growth stages under T1 were > 1, indicating that linked irrigation and drainage improved soil permeability.

Compared with the initial permeability coefficient, the relative permeability coefficients of clay, loam and sand under T1 increased by 1.12, 1.40 and 1.52, and 1.08, 1.32 and 1.41 times, at the bolling and maturity stages, respectively. Overall, the permeability coefficients of soils with different textures were higher than the initial values. Under T2, the K/K0 values of different soil textures at cotton seedling stage, bud stage and boll stage were >1, and the K/K0 values at the mature stage were <1, indicating that the soil permeability coefficient at the mature stage was lower than the initial permeability coefficient. Under T2, the permeability coefficients of clay, loam and sandy soil at bolling stage increased to 1.06, 1.14 and 1.21 times those of the initial permeability coefficients, respectively, and the permeability coefficients of clay, loam and sandy soil decreased to 0.88, 0.94 and 0.96 times those of the initial permeability coefficients at the mature stage, respectively. Compared with those seen under T2, the relative permeability coefficients of clay, loam and sandy soil under T1 at the bolling and mature stages increased by 5.66%, 22.81% and 25.62%, and 22.73%, 40.43% and 58.33%, respectively. Overall, the drip irrigation under plastic film technique combined with concealed pipe drainage technology (T1) effectively improved soil permeability and the cotton root soil environment.

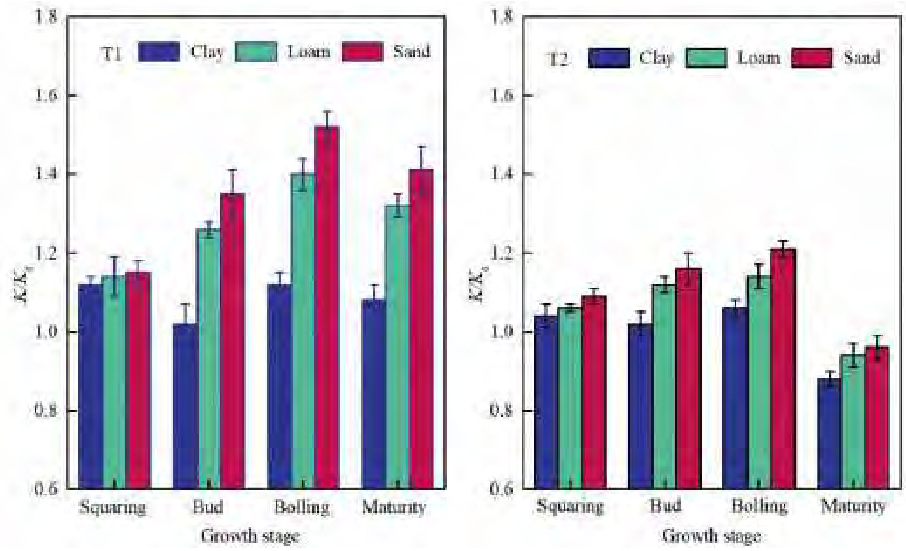

Figure 6. Changes in soil permeability at different growth stages of cotton under T1 and T2 treatments.

3.4 Soil pH

Under the T1 and T2 treatments, the pH values measured in the same soil layer of different soil textures were ranked as follows: clay > loam > sandy soil (Figure 7). The pH of the 0–60 cm layer in loam and sandy soil under T1 decreased gradually, while the pH value of the 60–100 cm layer increased. The combined irrigation and drainage treatment thus reduced the pH value of shallow soil. The soil pH value of the 0–60 cm layer in clay fluctuated without an obvious structure, and the soil pH value of the 60–100 cm layer increased gradually. Under T2, the pH value of the 0–60 cm layer in loam gradually increased, while that in the 60–100 cm layer gradually decreased. The change of soil pH value was consistent with the change in soil moisture. The pH value of the 0–60 cm layer in sandy soil gradually decreased, while the pH value of the 60–100 cm layer gradually increased with depth.

The average pH values for clay, loam and sandy soil in the 0–60 cm layer under T1 and T2 were 8.33, 8.05 and 7.99, and 8.77, 8.55 and 8.26, respectively. The average pH in the 0–60 cm layer of the clay, loam and sandy soil under T1 decreased by 5.02%, 5.85% and 3.27%, respectively, compared with the T2 treatment. Cotton roots were mainly distributed in 0–60 cm soil layer, and the linked irrigation and drainage treatment reduced the pH of the shallow soil and effectively improved the root growth environment for cotton, which will be of great significance to cotton growth and yield improvement.

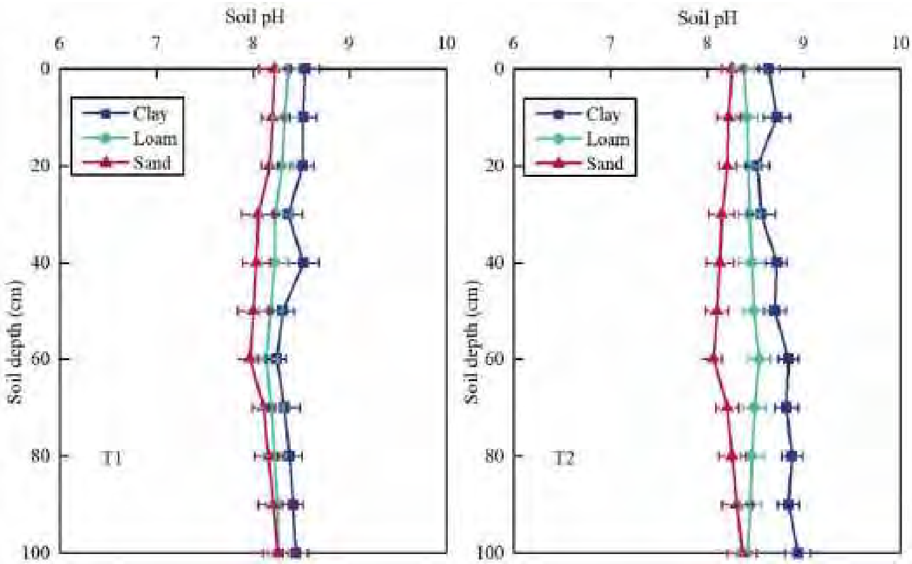

Figure 7. Soil pH values in various layers of soil with different textures.

3.5 Growth Characteristics and Quality of Cotton

The cotton growth indexes at the flowering and boll stage (July 25) and cotton quality at the mature stage (September 25) under T1 and T2 are shown in Table 3. The plant height, stem diameter, leaf area index and dry matter mass of cotton grown in soils of different texture under T1 and T2 were ranked as follows: loam > clay > sandy soil; the differences in these values seen between the soil textures under the same treatment were significant. Among the different treatments on soil with the same texture, the growth index of cotton in loam and clay under T1 was significantly higher than that under T2, but there was no significant difference in the cotton growth index in sandy soil. The plant height, stem diameter, leaf area index and dry matter mass of cotton treated with T2 in loamy soil were 97.26%, 95.16%, 89.47% and 98.74% of those in T1, respectively.

Except for elongation and lint percentage, the other indexes of cotton quality under T1 and T2 with different soil textures were ranked as follows: loam > clay > sandy soil. There was no significant difference between loam and clay in elongation and lint percentage, but both values were significantly larger than those in sandy soil. The cotton quality under T1 and T2 using the same soil texture showed no significant difference between clay and sandy soil, but the values for the average length of the upper half, micronaire value and fracture-specific strength under T1 in loamy soil were higher by 2.80%, 6.00% and 8.31%, respectively, than those under T2. In general, the combination of irrigation and drainage greatly impacted the growth and quality of cotton in the loam and clay soil. Compared with clay and sandy soil, the growth and quality of cotton in loam was higher, indicating that soil texture has an important impact on the growth of this crop.

Table 3. Analysis of the agronomic characters of growth and quality in cotton using different soil textures under T1 and T2.

	Soil Texture	Cotton Growth Characteristics				Cotton Quality					
		Plant Height (cm)	Plant Stem (mm)	Leaf Area Index	Dry Matter (g)	Upper Half Mean Length (m)	Length Uniformity Index (%)	Micro-naire	Breaking Strength (Cn/ Tex)	Elongation (%)	Lint (%)
T1	Clay	69.3 b	10.9 b	3.2 b	69.8 b	27.9 c	84.4 b	4.8 c	26.5 c	6.8 a	40.4 a
	Loam	72.9 a	12.4 a	3.8 a	71.6 a	33.1 a	88.8 a	5.3 a	32.6 a	7.2 a	41.8 a
	Sand	54.2 d	9.4 d	2.3 d	61.4 d	28.4 d	75.5 c	3.9 d	21.2 d	5.9 b	36.8 b
T2	Clay	64.1 c	10.5 c	2.8 c	68.7 c	28.4 c	83.3 b	4.7 c	25.3 c	6.7 a	39.4 a
	Loam	70.9 b	11.8 b	3.4 b	70.7 b	32.2 b	87.3 a	5.0 b	30.1 b	7.0 a	41.5 a
	Sand	53.6 d	8.6 d	2.1 d	54.4 d	28.5 d	72.7 c	3.7 d	20.4 d	5.6 b	36.3 b

Note: the lower case letters within columns indicate significant differences at the 0.05 level.

3.6 Cotton Yield and Water Use Efficiency

The yields of seed cotton under T1 and T2 in different soil textures showed that loam > clay > sandy soil, and there were significant differences among the different soil textures (Figure 8). Under T1 and T2, the yield of seed cotton in clay and sandy soil was 87.50% and 80.97%, and 92.25% and 84.49%, of that in loam, respectively. Moreover, using the same soil texture, the yield of seed cotton in loam under T1 was 6.37% higher than that under T2, and this difference was significant. There was no significant difference in the cotton yield between T1 and T2 in clay and sandy soil.

The water use efficiency of different soil textures under T1 and T2 was ranked as follows: loam > clay > sand soil, and there were significant differences between different soil textures (Figure 8). Under T1 and T2, the water use efficiency of the clay and sandy soil was 79.57% and 67.44%, and 87.42% and 74.24%, of that in loam, respectively. The water use efficiency under T1 in loam was significantly (13.70%) higher than that under T2. There was no significant difference, however, in the water use efficiency of clay and sand between T1 and T2. Cotton yield and water use efficiency under T1 and T2 in soils of different texture were ranked as follows: loam > clay > sandy soil. In all, linking irrigation and drainage had a significant impact on cotton yield and water use efficiency. The drip irrigation under plastic film technique combined with concealed pipe drainage technology was able to improve soil water, nutrient and gas conditions, with consequent increases in cotton growth.

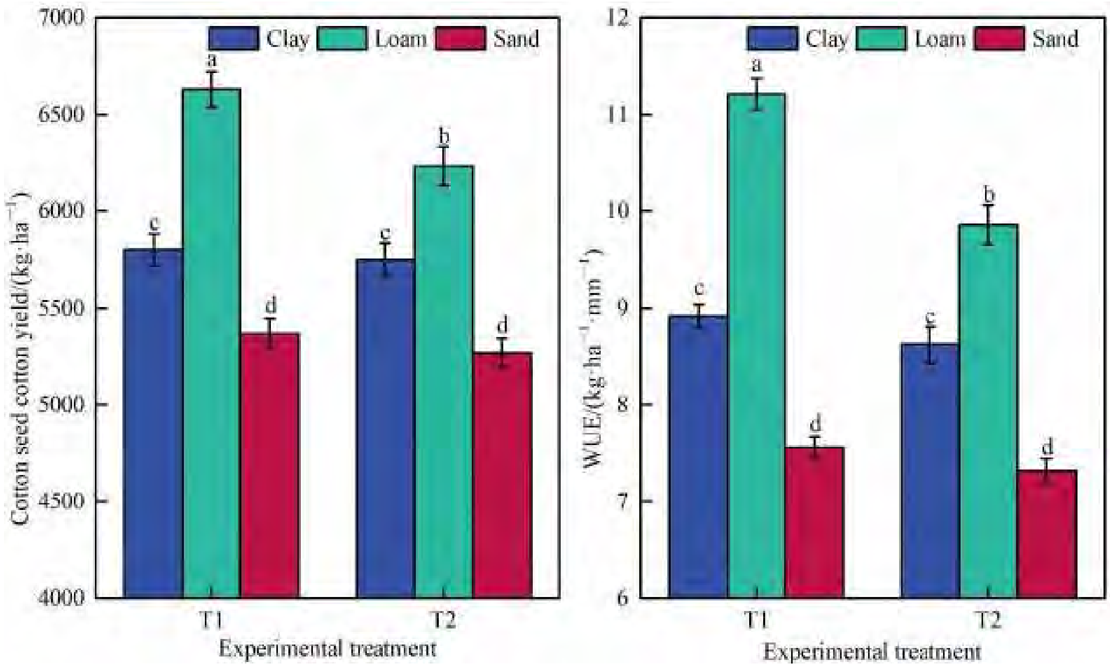

Figure 8. Effects of T1 and T2 treatments on cotton seed cotton yield and water use efficiency. Note: Different superscript letters (a, b, c and d) indicate significant differences between treatments in a year ($p \leq 0.05$).

4. Discussion

Combined irrigation and drainage treatment in different soil textures had an obvious impact on the soil environment. As the main area for crop root growth and nutrient absorption, changes in soil water, nutrient levels, permeability and pH have various effects on crop growth. Soil texture influences the characteristic soil water curve due to differences in the particle composition. The higher the soil clay content, the slower the water infiltration and the smaller the scope of the wetting body, which in turn increases the soil water content and soil water retention (Zhang et al., 2016). By studying the effect of soil texture on the soil moisture status, it was concluded that evidence of rapid and deep infiltration in 'dry' texture-contrast soils has implications for water and solute management (Hardie et al., 2010). Our research showed that the soil moisture content of clay and loam in different soil layers under T1 and T2 was significantly higher than that in sandy soil; thus, compared with sandy soil, clay and loam have better water retention. The moisture content of different soil textures under T1 was slightly higher than that under T2, mainly because the sand content of the sandy soil was high, which was conducive to water penetration, whereas the clay has fine soil particles, producing a large surface area and large water absorption capacity; these findings were similar to pre-vious research results (Zhang et al., 2008). Under combined irrigation and drainage, the amount of salt discharged by the concealed pipe accounts for 28.90% of the salt content of soil at a depth of 0–80 cm (Shi et al., 2020). Using linked irrigation and drainage, the total salt content in the root layer was previously found to decrease by 50.34% at a depth of 0–200 cm (Liu et al., 2018). Soil texture controls salinity by regulating the composition of the soil microbial community (She et al., 2021). Our study showed that the average salt content of clay, loam and sandy soil in the 0–60 cm layer under T1 treatment decreased by 14.09%, 14.21% and 12.35%, respectively, compared with T2. The combined irrigation and drainage treatment therefore reduced the salt content of the shallow soil. Using the combined irrigation and drainage treatment, the soil salt content at the end of the cotton growth period decreased by 16–43% compared with that before sowing (Yang et al., 2020). There was a positive correlation between sand content and soil permeability. The higher the sand content, the faster the water infiltration rate and the deeper the infiltration depth, with the clay content and its characteristics leading to the opposite (Zhong et al., 2014). Our research showed that the K/K0 of different soil textures at different growth stages of cotton under T1 and T2 was ranked as follows: sandy soil > loam > clay. Under T1, the K/K0 of different soil textures at different cotton growth stages was >1. Hence, linked irrigation and drainage improved both soil permeability and the cotton root soil environment.

Soil texture has a great impact on soil pH due to compositions of particles. The proportion of silt particles in soil has a very significant negative correlation with soil pH (Tang et al., 2020). Our study showed that the pH value of the same soil layer under different soil textures under T1 and T2 was ranked as follows: clay > loam > sandy soil. Under T1, the average pH value of clay, loam and sandy soil in the 0–60 cm soil layer was reduced by 5.02%, 5.85% and 3.27%, respectively, compared with T2. Cotton roots were mainly distributed in the 0–60 cm soil layer. The combined irrigation and drainage treatment reduced the pH value of this shallow soil and effectively improved the root growth environment. Sandy soil has many large pores, few small pores, a weak capillary effect, strong infiltration capacity and poor water retention. Salt infiltrates rapidly with water, increasing the pH value of deep soil. Clay soil has high content of fine particles, slow infiltration of irrigation water, high water absorption and shows expansion of the clay particles, which hinders capillary water movement. At the same time, there is a significant capillary effect between the clay particles, although water permeability is slow, and the pH value of the 0–100 cm soil fluctuates (Li et al., 2018). A similar situation was found in our study. The pH value of the 0–60 cm soil layer in clay fluctuated subtly, while the soil pH value of the 60–100 cm layer increased gradually.

Good soil water and fertilizer holding capacity and aeration performance are beneficial to crop root growth and water, and nutrient absorption levels, which im-prove crop yield. The water holding capacity, permeability and aeration of soil are important factors that affect drainage under unsaturated conditions Eliminating the hysteresis effect and capillary barrier around the drainage pipe and adjusting the water holding capacity, permeability and aeration of the soil structure using a new sub-surface drainage structure may enhance the drainage efficiency of subsurface drainage pipes in saturated-unsaturated zones (Li et al., 2021). Compared with clay and sandy soil, cotton in loamy soil produces the largest single bolls, has a high lint percentage, forms more bolls, and has the highest yield of seed cotton and lint (Ma et al., 2011). The yield of seed cotton and irrigation water productivity in loam soil were significantly higher than those in clay and sandy soil (Jalota et al., 2006; Su et al., 2014). The comprehensive growth index of cotton planted in loam with different soil texture is better (Wang et al., 2017). When fertilizer rates were the same, soil NO^{-}_{3}-N was distributed more uniformly in the loam soil than in the sandy soil (Ma et al., 2017). Our study showed that the plant height, stem diameter, leaf area index and dry matter mass of cotton in different soil textures under T1 and T2 were ranked as follows: loam > clay > sandy soil. The growth indexes of loam and clay cotton under T1 were significantly higher than those under T2, and there was no significant difference in the cotton growth indexes in the sandy soil. The cotton yield and water use efficiency under T1 and T2 in soils of different texture was ranked as follows: loam > clay > sandy soil, and there were significant differences among different treatments. The cotton yield and water use efficiency under T1 in loam were significantly higher than those under T2, and the research results were similar to those of previous scholars in different regions (Razzaghi et al., 2012). With respect to water saving and yield, the proportion of cotton planting in loamy soil should be increased under the same irrigation treatment, and the water and salt of different soil textures should be adjusted through by combining irrigation and drainage, so as to effectively improve the root growth environment of crops. This will play a positive role in increasing crop yield, improving water and fertilizer utilization efficiency and promoting agricultural production. Compared with previous studies, our research systematically explains the effects of combined irrigation and drainage technology on soil moisture, salinity, permeability, soil pH and cotton growth, which provides a new idea for promoting agricultural water saving and saline alkali land improvement.

5. Conclusions

This study evaluated the effects of soil texture on soil water and salt distribution, permeability, pH, cotton growth and water use efficiency using a combined irrigation and drainage technique in the Xinjiang oasis agroecosystem. We came to the following conclusions.

•The water retention of clay and loam was better than that of sandy soil. Combined irrigation and drainage increased the soil water holding capacity and reduced the shallow soil salt content. Combined irrigation and drainage reduced the pH value of the shallow soil and effectively improved the root growth environment of cotton.

•Under the combined irrigation and drainage and conventional drip irrigation treatment, the K/K0 values for different soil textures at the different growth stages of cotton were sand > loam > clay, and the K/K0 values under the combined irrigation and drainage treatment were >1. Combined irrigation and drainage improved soil permeability.

•The growth index, seed cotton yield and water use efficiency of cotton under the combined irrigation and drainage and conventional drip irrigation treatments in different soil textures were loam > clay > sandy soil. The cotton growth indexes of loam and clay under the combined irrigation and drainage treatment were significantly higher than those under the conventional drip irrigation treatment.

•In loamy soil, the cotton yield and water use efficiency of the combined irrigation and drainage treatment were significantly higher than that using the conventional drip irrigation treatment. The cotton yield and water use efficiency of the combined irrigation and drainage treatment were 6.37% and 13.70% higher than those under the conventional drip irrigation treatment, respectively.

The combination of irrigation and drainage effectively improved the root growth environment of cotton in different soil textures, improved the yield and quality of cot-ton and provided a new idea to use in promoting agricultural water saving and saline alkali land management.

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DIAGNOSIS OF COMPREHENSIVE INDEX OF WATER DEFICIT OF WINTER-WHEAT BASED ON UAV REMOTE SENSING AND MACHINE LEARNING

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ABSTRACT

To monitor crop water condition quickly and accurately, water deficit experiments were set up with winter wheat in 2021 and 2022. The unmanned aerial vehicle (UAV) multispectral and thermal infrared images of six growth stages of winter wheat were acquired. Firstly, the vegetation indices and temperature indices were constructed. Secondly, the correlation between the indices and stomatal conductivity (GS), soil water content (SWC, 0-40cm), and the comprehensive index of water deficit (CIWD) composed of GS and SWC were analyzed. Finally, GS, SWC and CIWD prediction models were established by using three machine learning methods: partial least squares(PLS), support vector machines (SVM) and Residual Neural Network (ResNet). The results showed that: (i) the indices had a high correlation with Gs, SWC and CIWD, most reached a significant level (P<0.05); (ii) the accuracy of CIWD models were higher than GS models and SWC models. Compared with PLS and SVM, ResNet had the best effect, the coefficient of determination (R^2) of CIWD models increased from 0.663 to 0.884 in 2021 and 0.671 to 0.852 in 2022, respectively; (iii) Among the three models, the accuracy of the CIWD models built by ResNet performed best. The models modelling R^2, mean absolute error (MAE), root mean square error (RMSE) and normalized root mean square error (NRMSE) were 0.884, 0.047, 0.058, 8.608% in 2021 and 0.856, 0.050, 0.062, 9.221% in 2022, respectively. The results of the two-year studies were consistent and accurate. Therefore, using multimodal UAV remote sensing can provide a feasible and accurate method for the diagnosis of water deficit and irrigation decision-making in winter wheat.

Keywords: Winter wheat, Water deficit, UAV remote sensing, Machine learning

1. Introduction

Wheat is the food crop with the largest planting area and the widest distribution in the world. Irrigation is vital for agricultural production, and a substantially higher crop yield was obtained on irrigated land than on rain-fed land in China. However, available water resources for irrigation are increasingly limited. For example, the North China Plain, which has a semi-arid climate and produces nearly 75% of the wheat in China, has long been suffering from severe water shortages. The exploitation of groundwater accounts for 70% of the total water utilization, and 79% of the groundwater is pumped for irrigated agriculture.

To achieve the development goals of carbon neutrality and carbon peaking in the world today, it is imperative to implement precision irrigation. But this requires accurate judgment of crop water deficit. Traditional crop information acquisition relies on many field samplings, which is costly, time-consuming, and labour-intensive, and the timeliness and accuracy of yield measurement results cannot be guaranteed. Satellite remote sensing can monitor crop growth in a large area, but its estimation accuracy is easily affected by clouds, weather, etc., and the spatial and temporal resolution of remote sensing images is low. UAV remote sensing has the characteristics of wide coverage, short measurement period, low cost, and strong manoeuvrability. In recent years, it has been widely used in pest identification, crop growth monitoring, yield estimation, crop lodging judgment, et al., providing a new scale for crop information acquisition.

The research on the diagnosis of water deficit by UAV thermal imaging started earlier in foreign countries, and most of the research objects are concentrated on economic crops such as fruit trees and grapes. Baluja et al. proved that there is a strong correlation between the canopy temperature obtained by the thermal infrared camera mounted on the UAV and the ground measured value, and it is feasible to judge the water deficit based on the collected canopy temperature data. Gonzalez-Dugo et al. used thermal infrared cameras to collect remote sensing images of five fruit trees, including apricot, peach, and citrus, and obtained the diurnal variation of the fruit tree canopy air temperature difference. The correlation of crop water stress index (Crop Water Stress

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Index, CWSI) is given, which provides help for irrigation management and decision-making. Santesteban et al. obtained the CWSI from the images collected by the thermal infrared camera and pointed out that the CWSI has a good correlation with the leaf water potential and stomatal conductance of grapes. In domestic research reports, Sun Sheng et al. used a UAV equipped with a thermal infrared camera to monitor the continuous irrigation area and drought-stressed area of walnut orchards and showed that the canopy air temperature difference was negatively correlated with soil moisture content. The moisture content model has high accuracy.

Studies have shown that the photochemical reflectance index (PRI) is significantly correlated with photosynthetic indicators such as stomatal conductance and leaf water potential of citrus trees. Compared with hyperspectral cameras, multispectral cameras have lower cost and simpler data processing, and many scholars have explored the feasibility of this sensor in water deficit diagnosis. Espinoza et al. used a drone equipped with a multispectral camera to collect remote sensing images of vineyards and pointed out that the Green normalized difference vegetation index (GNDVI) was significantly correlated with stomatal conductance. Chen Junying et al. carried out remote sensing monitoring of cotton at different times of the day and found that there is a correlation between photosynthetic parameters such as transpiration rate, stomatal conductance, and intercellular carbon dioxide concentration of cotton and its spectral reflectance. Zhang Zhitao et al. confirmed that the multispectral vegetation index can invert the soil moisture content of maize roots, and Tan Chengxuan et al. and Zhang et al. confirmed that the multispectral index of corn canopy also has a linear correlation with CWSI.

To improve the accuracy of the crop water deficit diagnosis model, scholars have constructed a multivariate data fusion model. Cheng et al. pointed out that the fusion of light, multispectral and thermal infrared data can make the soil water content model more accurate than the single-variable model. Zhou et al. used stomatal conductance as the water stress evaluation index and constructed a water stress diagnosis model for winter wheat by using the vegetation index and texture index selected by full subset regression. The results showed that the model constructed by the combination of vegetation index and image texture had the best effect it is good. Babaeian et al. integrated vegetation index and soil physical properties and used an automated machine learning algorithm (Automated Machine Learning, AutoML) to estimate the soil moisture content of wheat soil surface (2cm), near-surface (10cm) and root system (50cm). The results show that the soil water content model constructed using the combination of vegetation index and soil physical properties as input variables can capture field-scale changes in soil water content.

However, the stomatal conductance of crops is easily affected by the collection time and weather conditions. In addition, when planting large-scale plots, the soil water content may be uneven due to soil spatial variability, which provides difficulties for predicting water deficit. Therefore, this study aims to construct a comprehensive index of water deficit (CIWD) in the whole growth period and provides a reference for diagnosing the water deficit status of winter wheat by UAV remote sensing.

2. Materials and methods

2.1 Study area and experimental treatments

The experiments conducted at Zhuozhou (39.45° N and 115.85°E), Hebei Province, China. This area belongs to the semi-humid monsoon region of the warm temperate zone, with significant continental monsoon climate and seasonal temperature differences. The annual mean precipitation in the study area is about 563.3 mm, and the annual mean temperature is about 11.6℃. The experiment field was a sector with an angle of 60 degrees, and the radius of the sector was 140 meters, so the total area was about 1.03 hm^2.

The soil type is mainly sandy soil. The field water holding capacity was 0.21 cm^3/cm^3. The average mass fractions of silt, sand and clay in the 0-80 cm soil layer were 87.92%, 8.40% and 3.68%, respectively. And the mass ratios of organic matter, available phosphorus, available potassium, nitrate nitrogen, and ammonia nitrogen were 11.72 g/kg, 32.45 mg/kg, 54.98 mg/kg, 14.01 mg/kg, and 4.56 mg/kg, respectively.

The 2020-2021 winter wheat (2021 winter wheat) and the 2021-2022 winter wheat (2022 winter wheat) were both Nongda 212, with a row spacing of 15cm, and the sowing rate in 2021 and 2022 were 270 kg/hm2, 330 kg/hm2, sown on October 12, 2020, and October 10, 2021, respectively. The amount of organic fertilizer applied during sowing in 2021 was 22,500 kg/hm2, and no organic fertilizer was applied in 2022. All zones were fertilized uniformly based on typical cultural practices for yield potential. Specifically, the basal fertilizers mount of nitrogen(N), phosphorus (P2O5), and potassium (K2O) applied were 54, 138, and 81 kg /hm2, respectively.

Irrigation treatments were carried out from April to June in 2021 and 2022. Irrigation treatments plot was divided into 12 experimental areas, corresponding to 4 irrigation levels, namely W1 (extremely deficient), W2 (moderate deficient), W3 (slight deficient), W4 (adequate irrigation). Each experimental area was divided into 3 zones, so there were 36 zones of 6 m×6 m. The amount of irrigation in 2021 and 2022 was shown in Table 1. The nitrogen was applied by the fertigation system on March 30, April 25, May 10 in 2021, and on April 2, April 29, May 19 in 2022 with amount of 90 kg/hm2, 90 kg/hm2 and 20 kg/hm2, respectively.

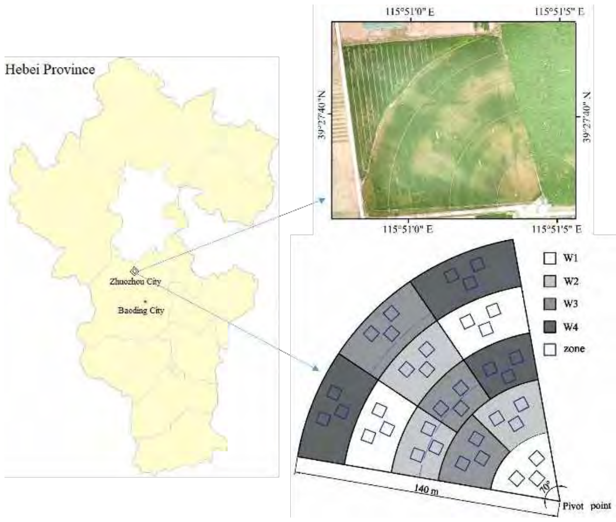


Figure. 1. Locations and treatments of the experiments in this study.

During the test period, irrigation was started in each treatment when the soil water content in the 0-40 cm soil layer of the W4 treatment was as low as 65%-70% FC. The irrigation system of the experimental site is a circular sprinkler and is equipped with a variable irrigation system. The irrigation amount of different treatments was changed by changing the walking speed of the center pivot sprinkler machine and the opening and closing time of the solenoid valve.

Table 1 Irrigation treatments and total irrigation and precipitation amount (mm) in 2021 and 2022

2021						2022				
Date	W1	W2	W3	W4		Date	W1	W2	W3	W4
Nov.16,2020	30	30	30	30		Nov.27,2021	30	30	30	30
Mar.30	20	25	30	40		Apr.2	20	25	30	40
Apr.17	10	17.5	25	30		Apr.17	10	17.5	25	30
Apr.25	20	25	30	40		Apr.27	20	25	30	40
May.1	10	17.5	25	30		May.17	10	17.5	25	30
May.10	20	25	30	35		May.19	20	25	30	35
May.17	20	25	30	35		May.27	20	25	30	35
May.24	20	25	30	35		-	-	-	-	-
Total amount	150	190	230	270		Total amount	130	165	200	235

2.2 UAV images acquisition

2.2.1 UAV remote sensing platform

The UAV platform is a DJI M300 Pro UAV (DJI, China) (maximum take-off weight of 9 kg, maximum payload 2.7 kg, max. flight time of 55 min without payload). Flights were performed in clear sky and low wind speed conditions, between 11:00 and 13:00 at local time. The app DIJ Pilot (DJI, China) was used for all flight planning, based on 75% forward and 75% side overlapping in image acquisition for the thermal imagery (see further). The flight height was 50m, flight speed was 2.1 m/s. The flight time, temperature, relative humidity, solar radiation, and wind speed were shown in Table 2.

Five Ground Control Points (GCPs) were set up in the test area for precise geometric correction of remote sensing images, and a high-precision GNSS receiver (M600 mini, Compass Navigation, China) was used to measure the precise coordinates and elevation of the GCPs. The GNSS receiver adopts RTK protocol. The positioning protocol adopted is Qianxun Find CM (Qianxun SI, China) with a horizontal accuracy of 2 cm and an elevation accuracy of 5 cm. Additionally, GCPs had been remained in the field during the entire growing season of winter wheat.

Table 2 The flight time of the UAV and the corresponding meteorological parameters

	2021						2022					
Date	Time	T[a] (℃)	RH（%）	RS (W/m^2)	WS (m/s)		Date	Time	T (℃)	RH（%）	RS (W/m^2)	WS (m/s)
Apr.6	12:05-12:30	19.8	42.8	391.9	0.8		Apr.8	11:30-11:55	19.5	54.6	668.1	0.5
Apr.22	12:25-12:50	16.1	72.1	686.9	1.2		Apr.15	12:45-13:00	19.4	27.1	788.1	1.2
Apr.30	12:45-13:10	14.8	54.2	610.6	1.8		Apr.25	13:00-13:25	26.0	65.7	649.4	0.3
May.7	12:10-12:35	25.7	24.1	818.1	1.0		May.4	12:25-12:50	31.4	38.1	814.4	0.8
May.11	12:35-13:00	25.6	52.3	751.9	1.3		May.11	11:45-12:10	19.5	49.6	538.5	1.4
May.27	12:10-12:35	28.6	27.9	906.9	1.5		May.26	11:45-12:10	32.6	13.5	800.4	1.5

[a]T, air temperature (℃); RH, relative humidity (%); RS, solar radiation (W/m^2); WS, wind speed (m/s).

2.2.2 Multispectral camera

Multispectral data were obtained with a Red Edge multispectral camera (Mica sense, Seattle, WA, USA). The camera is a global shutter sensor with a spectral band in the blue (465 to 485 nm), green (550 to 570 nm), red (663 to 673 nm), red edge (712 to 722 nm), and near-infrared (820 to 860 nm) regions of the electromagnetic spectrum. The focal length is 5.5 mm, resulting in a field of view of 47.2° and a ground sampling distance of is 3.5 cm at 50m fight height. During the flights, the camera was connected to the DLS-2 sensor, measuring GNSS position and downwelling light. The camera was set to take an image every 2 seconds. A radiometric whiteboard was photographed for radiometric correction using the multispectral camera before each flight.

2.2.3 Thermal camera

Simultaneously, a thermal infrared camera (Zenmuse H20T, DJI, China) collected thermal imagery. It is an integrated camera that contains 4 sensors for zoom, wide-angle, and metering and ranging. The thermal imaging camera is a radiometric microbolometer camera with a single band sensitive in the 8-14 μm spectral range, a temperature range of -40-150°C and a resolution of 640×512 pixels. Its lens has a focal length of 13.5 mm, resulting in a field of view of 40.6° and a ground sampling distance of is 4.5 cm at 50m fight height. Images were acquired every 2s.

2.2.4 Date processing

Pix4D Mapper was used to preprocess and the coordinates of five GCPs were input for terrain correction. The multispectral remote sensing images was combined with a solar light sensor and a radiometric correction whiteboard for radiometric correction, then pixel values of the multispectral images were converted into spectral reflectance values. The flight altitude, relative humidity, air temperature and reflectivity were input to process the thermal infrared remote sensing images. Then R-JEPG images were converted to TIFF. Finally, the TIFF images were stitched by Pix 4d. The specific indices were Ratio vegetation index (RVI), Normalized difference vegetation index (NDVI), Normalized difference red-edge (NDRE), Optimized soil adjusted vegetation index

(OSAVI), Green normalized difference vegetation index (GNDVI), Red-edge chlorophyll index (CIRE), Perpendicular vegetation index (PVI), Green optimal soil adjusted vegetation index (GOSAVI), Modified simple ratio (MSR), Modified soil adjusted vegetation index (MSAVI), Canopy temperature minus air temperature(Tc-Ta), Canopy temperature divided by air temperature(Tc/Ta) .

2.3 Ground data acquisition

2.3.1 Stomatal conductivity

GS of winter wheat flag leaves was measured using a stomatal conductometer (SC-1, METER, USA) from 11:00-12:00 on the day of UAV flight. The instrument was calibrated before measured every time, and the sensor probe was kept horizontally downward during measurement, and the GS on the back of the blade was uniformly measured. A total of 36 sets of GS data were collected in each growth stage, and the specific values are shown in Table 4. In the 2-year experiment, the GS of different irrigation treatments showed a trend of increasing and then decreasing with the growth. The peak values of W3 and W4 were heading stage and flowering stage, but jointing stage was peak for W1 and W2 due to the accumulation effect of water deficit. There were obvious differences among different irrigation treatments, and the GS showed a decreasing trend with the increase of water deficit.

Table 3 GS of irrigation treatments at different growth stages (mmol/s^{2}m)

Growth stages	2021					2022			
	W1	W2	W3	W4		W1	W2	W3	W4
Tilling	187±44c	212±37c	274±37b	324±43a		175±30c	177±28bc	209±33abc	222±40a
Jointing	251±37c	273±39c	348±45b	408±35a		250±37b	278±40b	333±40a	368±48a
Booting	212±36d	287±53c	362±36b	428±64a		206±60c	239±33c	333±37b	389±54a
Heading	181±48d	231±61c	366±37b	503±56a		195±41d	288±31c	439±46b	487±54a
Flowering	151±40d	238±30c	335±37b	480±33a		165±44d	250±46c	411±38b	504±47a
Filling	129±28d	161±34c	311±24b	339±25a		120±24b	146±33b	259±31a	272±47a

2.3.2 Soil water content

Trime (Trime-T3 TDR, Germany) was used to monitor SWC at depths of 0-20 cm and 20-40 cm. The buried position of the Trime tube was in the center of the zone. The soil was extracted with a soil drill next to the Trime tube, and SWC of Trime was corrected with the dried soil samples. The average value of SWC at the depth of 0-40cm soil layer are shown in Table 4.

Table 4 The average of SWC in the 0~40cm soil layer

Growth stages	2021					2022			
	W1	W2	W3	W4		W1	W2	W3	W4
Tilling	0.13±0.01c	0.15±0.01b	0.16±0.01b	0.17±0.02a		0.11±0.01b	0.13±0.02b	0.13±0.02b	0.15±0.02a
Jointing	0.12±0.02b	0.12±0.02b	0.15±0.03ab	0.16±0.02a		0.10±0.02b	0.12±0.01b	0.12±0.01a	0.13±0.01a
Booting	0.12±0.02b	0.12±0.02b	0.13±0.02b	0.15±0.02a		0.09±0.02c	0.11±0.01b	0.11±0.01b	0.13±0.02a
Heading	0.09±0.01c	0.10±0.02bc	0.11±0.01b	0.14±0.03a		0.10±0.02b	0.11±0.02b	0.11±0.01b	0.13±0.02a
Flowering	0.10±0.01c	0.11±0.02c	0.13±0.01b	0.16±0.02a		0.08±0.01b	0.09±0.01b	0.10±0.01b	0.13±0.02a

Filling	0.12±0.02b	0.12±0.02b	0.13±0.01b	0.16±0.02a		0.06±0.01c	0.07±0.01c	0.09±0.01b	0.11±0.01a

2.3.3 Meteorological parameters

A weather station (HOBO U30, Oneset, USA) was installed at the experimental site to collect meteorological parameters (recorded every 1 h), including wind speed, precipitation, air temperature, relative humidity, solar radiation and so on

2.4 Machine learning algorithms

PLS determines a linear regression model by projecting predictor and observation variables into a new space, which can avoid potential problems such as non-normal distribution of data, uncertainty in factor structure, and unrecognized models.SVM is a supervised machine learning algorithm that implements classification and regression by constructing a hyperplane or set of hyperplanes in a high-dimensional or infinite-dimensional space. ResNet is characterized by being easy to optimize and being able to increase accuracy by adding considerable depth. The internal residual block uses skip connections to alleviate the gradient disappearance problem caused by increasing depth in deep neural networks.

2.5 Model establishment and accuracy evaluation

CIWD was obtained by normalizing the GS and SWC of each growth stage, and the calculation formula is shown in equation (1). Prediction models of stomatal conductance, soil moisture content and comprehensive indexes were constructed in single growth period and whole growth period respectively by PLS, SVM and ResNet algorithms. 25 groups were randomly selected from the 36 groups of sample data as the model training set, and the remaining 11 groups were used as the validation set, and the regression program was written by Python.

$$CIWD_i = \frac{1}{2}\times\frac{GS_i}{GS_{max}} + \frac{1}{2}\times\frac{SWC_i}{SWC_{max}} \qquad (1)$$

where $CIWD_i$ is the water deficit index, GS_i and SWC_i are stomatal conductance and soil water content, and GS_{max} and SWC_{max} are the maximum values of stomatal conductance and soil water content in the growth stage.

The coefficient of determination (R2), average absolute error (MAE), root mean square error (RMSE), and standard root mean square error (NRMSE) were used to evaluate the reliability and accuracy of models' prediction results. Statistically, higher R2 and smaller MAE, RMSE and NRMSE, the higher the prediction accuracy of the model. The simulation effect evaluation was divided into 4 levels according to the NRMSE: excellent (NRMSE≤10%), good (10%＜NRMSE≤20%), suitable (20%＜NRMSE≤30%), and poor (NRMSE＞30%).

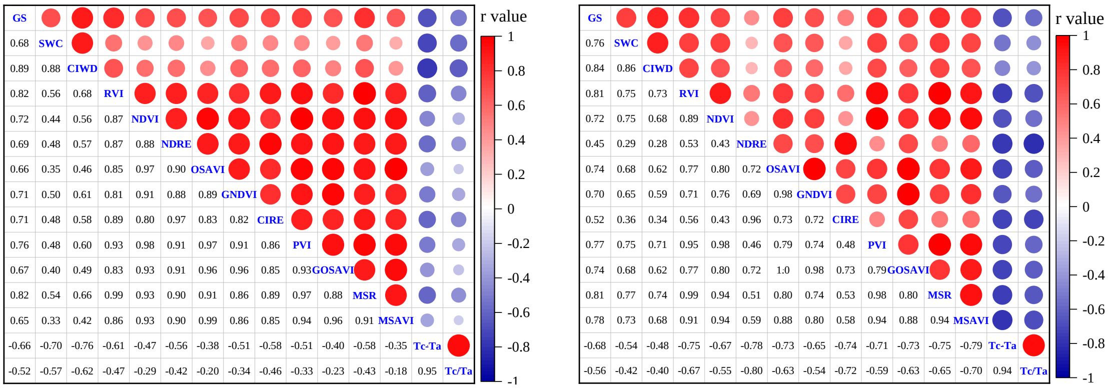
3. Result and discussion

3.1 Result of Pearson correlation coefficient

Figure 2(a) and (b) were the Pearson correlation coefficient matrices of GS, SWC, CIWD and VIs in 2021 and 2022, respectively. RVI, NDVI, NDRE, OSAVI, GNDVI, CIRE, PVI, GOSAVI, MSR, and MSAVI were significantly positively correlated with GS, SWC and CIWD, respectively. But Tc-Ta, Tc/Ta were significantly negatively correlated with GS, SWC and CIWD, respectively. There was a positive correlation between GS, SWC, and CIWD. In 2021 and 2022, the correlation coefficient between the indices and GS was bigger than 0.52 and 0.45, respectively, and the biggest correlation indices were RVI and MSR, with correlation coefficient of 0.82.

The correlation coefficients between the indices and SWC were bigger than 0.33 and 0.29, respectively. In 2021, Tc-Ta had the biggest correlation with correlation coefficient of 0.70, but in 2022, MSR had the biggest correlation with correlation coefficient of 0.77. The correlation coefficients between the indices and CIWD were bigger than 0.42 and 0.28, respectively.

In 2021, Tc-Ta had the biggest correlation with correlation coefficient of 0.76, but in 2022, MSR had the biggest correlation with correlation coefficient of 0.74, which was like SWC.The correlations between the indices and the three indicators were GS, CIWD, SWC from big to small, and the most correlated indices were RVI and NDVI.



（a）2021 （b）2022

Figure.2 Correlation diagram of GS, SWC and CIWD with vegetation indices and temperature indices

3.2 Estimation model of GS

Taking the selected vegetation indices as the input variable, the PLS, SVM, and ResNet algorithms were used to construct the GS models for different growth stages in 2021 and 2022, respectively. The results of the model training set are shown in Table 5. At tillering stage in 2021, the accuracy of the PLS was similar with SVM model, and the accuracy of the ResNet model was higher than that of the PLS and SVM, but the NRMSE of the ResNet model in 2021 and 2022 were 10.492% and 10.814%, respectively. The NRMSE of three models were at a good level in the jointing stage, except for the SVM model in 2022. At this time, the NRMSE of the GS model constructed by the ResNet in 2021 was 8.567%, reaching an excellent level, and the accuracy of the rest of the models were at a good level. At booting stage, heading stage and flowering stage, the accuracy of the three models was relatively stable.

Table 5 Results of training set of GS

Year	Growth stages	PLS				SVM				ResNet			
		R^2	MAE (mmol/s²m)	RMSE (mmol/s²m)	NRMSE (%)	R^2	MAE (mmol/s²m)	RMSE (mmol/s²m)	NRMSE (%)	R^2	MAE (mmol/s²m)	RMSE (mmol/s²m)	NRMSE (%)
2021	Tilling	0.699	27.481	35.381	14.333	0.730	26.583	33.51	13.575	0.839	21.490	25.907	10.492
	Jointing	0.657	35.891	41.704	13.110	0.658	31.426	41.638	13.090	0.853	22.635	27.248	8.567
	Booting	0.736	39.929	46.828	14.327	0.813	33.247	39.412	12.058	0.912	22.657	27.065	8.281
	Heading	0.924	36.038	40.470	12.992	0.931	31.305	38.533	12.369	0.971	19.315	25.099	8.057
	Flowering	0.902	32.158	41.579	13.667	0.927	31.474	35.876	11.793	0.961	19.905	26.277	8.638
	Filling	0.878	26.549	33.353	14.653	0.887	21.729	28.688	12.603	0.944	14.401	20.247	8.895
	All	0.798	40.909	50.084	17.242	0.782	43.152	52.028	17.912	0.902	28.511	34.907	12.018
2022	Tilling	0.400	20.321	27.901	13.867	0.54	18.362	24.422	12.138	0.635	16.048	21.758	10.814
	Jointing	0.606	34.942	41.474	13.515	0.625	34.893	40.495	13.196	0.778	27.119	31.105	10.136
	Booting	0.684	39.149	47.238	16.073	0.809	28.965	36.733	12.498	0.892	22.426	27.669	9.414
	Heading	0.890	37.157	42.767	12.235	0.93	28.054	34.083	9.751	0.944	24.593	30.664	8.773
	Flowering	0.818	44.124	55.788	17.066	0.872	36.524	46.786	14.312	0.932	26.813	34.038	10.412
	Filling	0.734	31.644	40.13	21.088	0.810	27.482	33.943	17.836	0.945	13.353	18.262	9.600
	All	0.732	46.022	58.951	21.231	0.826	37.792	47.437	17.084	0.907	28.625	34.673	12.487

The NRMSE of the PLS model varied from 12.992% to 14.327%, the NRMSE of the SVM model varied from 11.793% to 12.369%, and the NRMSE of the ResNet model varied from 8.057% and 8.638%. And the accuracy of the ResNet model was significantly higher than that of PLS and SVM, which was excellent. The accuracy of the SVM model was slightly higher than that of the PLS. During the filling period, the accuracy of the three models decreased, but the accuracy of the ResNet model was still excellent. Modeling after mixing the data from 6 reproductive stages, although the R2 was equivalent to the improvement of some single growth stages, for the PLS and SVM models, the NRMSE of the single growth stage was lower than that of any single growth stages. And the NRMSE of ResNet was higher than tillering stage.

Figure 3 showed the results of the validation set of GS. Similar to the results of the training set, in the 2-year experiment, the model prediction accuracy of GS increased first and then decreased with the growth of wheat. The prediction accuracy of PLS and SVM in different growth stages was similar, while the prediction accuracy of ResNet was significantly higher than these two models.

For the multi-growth stages, although the sample size of the model increased, the accuracy decreased. It can also be seen from Table 4 that the stomatal conductance of winter wheat showed a trend of increasing first and then decreasing throughout the growth cycle, while the vegetation indices increased in the later period. It tends to be saturated and shows a stable trend, so the prediction accuracy of stomatal conductance in the multi-fertile period not improved significantly.

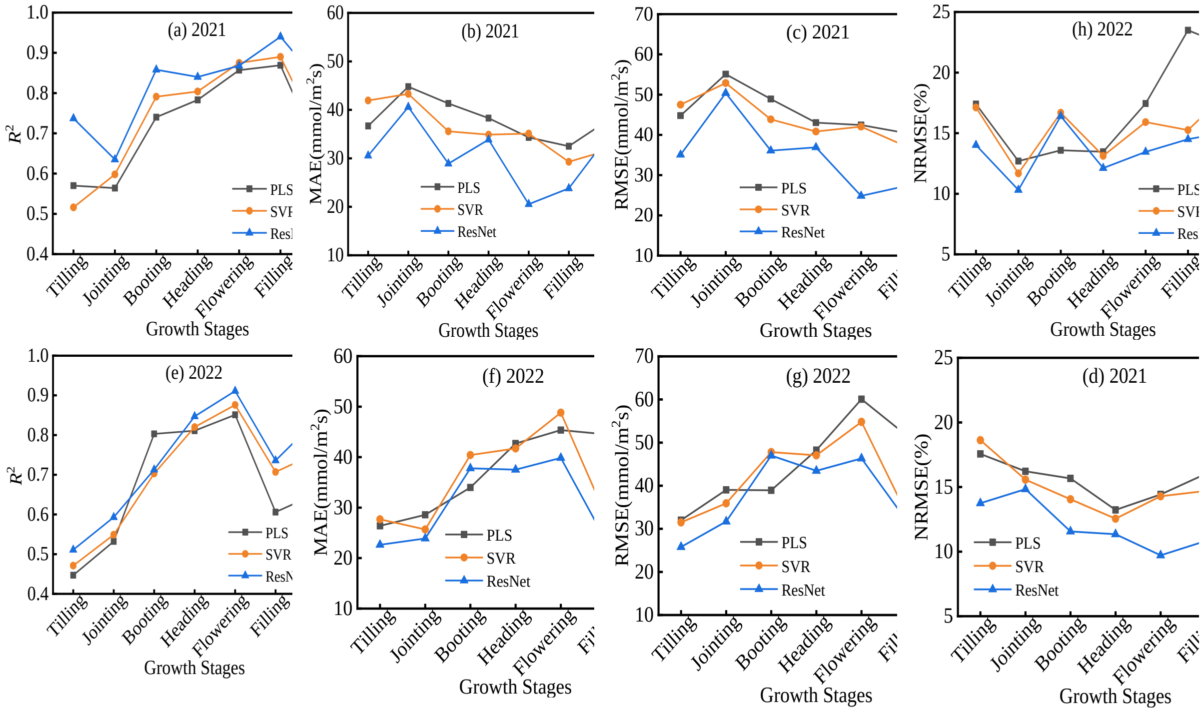


Figure 3. Results of validation set of GS

3.3 Estimation model of SWC

Table 6 showed the training set results of the SWC models for the soil 0-40cm soil layer in 2021 and 2022. In 2021, with the growth of winter wheat, the accuracy of SWC prediction model showed a trend of first decreasing, then increasing and then decreasing. The accuracy of the three algorithms all reached their peaks during the flowering stage. In 2022, the prediction accuracy of the model showed a trend of increasing first and then decreasing. The PLS algorithm peaked at the booting stage (NRMSE was 9.923%), the SVM algorithm was at the jointing stage (NRMSE was 9.511%), and the ResNet algorithm was at the flowering stage (NRMSE was 6.927%). The accuracy of the prediction model of SWC in the whole growth stage constructed by the ResNet algorithm reached an excellent level in 2021 (NRMSE of 8.877%) and 2022 (NRMSE of 8.827%).

Table 6 Results of training set of SWC

Year	Growth stages	PLS				SVM				ResNet			
		R^2	MAE (cm^3/cm^3)	RMSE (cm^3/cm^3)	NRMSE (%)	R^2	MAE (cm^3/cm^3)	RMSE (cm^3/cm^3)	NRMSE (%)	R^2	MAE (cm^3/cm^3)	RMSE (cm^3/cm^3)	NRMSE (%)
2021	Tilling	0.297	0.014	0.016	10.787	0.256	0.013	0.016	10.764	0.348	0.012	0.014	9.164
	Jointing	0.636	0.014	0.016	12.362	0.618	0.013	0.015	11.213	0.774	0.008	0.011	8.628
	Booting	0.431	0.012	0.015	11.458	0.542	0.010	0.014	10.279	0.727	0.007	0.011	7.93
	Heading	0.726	0.010	0.013	11.585	0.751	0.010	0.013	11.049	0.879	0.006	0.009	7.678
	Flowering	0.797	0.009	0.013	9.943	0.842	0.008	0.011	8.768	0.917	0.005	0.008	6.368
	Filling	0.351	0.013	0.016	12.075	0.253	0.014	0.017	12.959	0.675	0.008	0.011	8.553
	All	0.503	0.015	0.018	13.743	0.594	0.013	0.016	12.416	0.793	0.009	0.012	8.877
2022	Tilling	0.281	0.013	0.016	12.189	0.325	0.010	0.014	10.751	0.384	0.010	0.013	10.489
	Jointing	0.36	0.010	0.012	10.237	0.447	0.010	0.011	9.511	0.494	0.008	0.011	9.100
	Booting	0.83	0.009	0.011	9.923	0.801	0.009	0.012	10.72	0.881	0.007	0.009	8.308
	Heading	0.588	0.010	0.012	10.264	0.618	0.010	0.012	9.887	0.770	0.007	0.009	7.667
	Flowering	0.754	0.008	0.012	10.517	0.774	0.009	0.011	10.084	0.893	0.005	0.008	6.927
	Filling	0.724	0.008	0.011	11.879	0.723	0.008	0.011	11.894	0.860	0.010	0.010	8.350
	All	0.619	0.011	0.014	12.706	0.643	0.011	0.014	12.299	0.840	0.008	0.009	8.227

Figure 4 showed the results of SWC validation set. The results of the validation set were basically consistent with the training set. In 2021, R^2 reached the best value at heading stage, while MAE, RMSE and NRMSE all reached the best value at flowering stage. In 2022, R^2 and NRMSE reached the best value at the grain filling stage, while MAE reached the best value at the flowering stage. Due to the small difference of SWC in tillering stage, the prediction accuracy of the three algorithms was at a low level and the difference was small.

With the growth of winter wheat, the degree of crop water deficit caused by the irrigation treatments gradually increased, and the water demand of the crop could not be met. At this time, the difference in SWC between different treatments also became larger, and the prediction accuracy increased at this time. Compared with the three algorithms, the prediction accuracy of ResNet was higher than that of PLS and SVM.

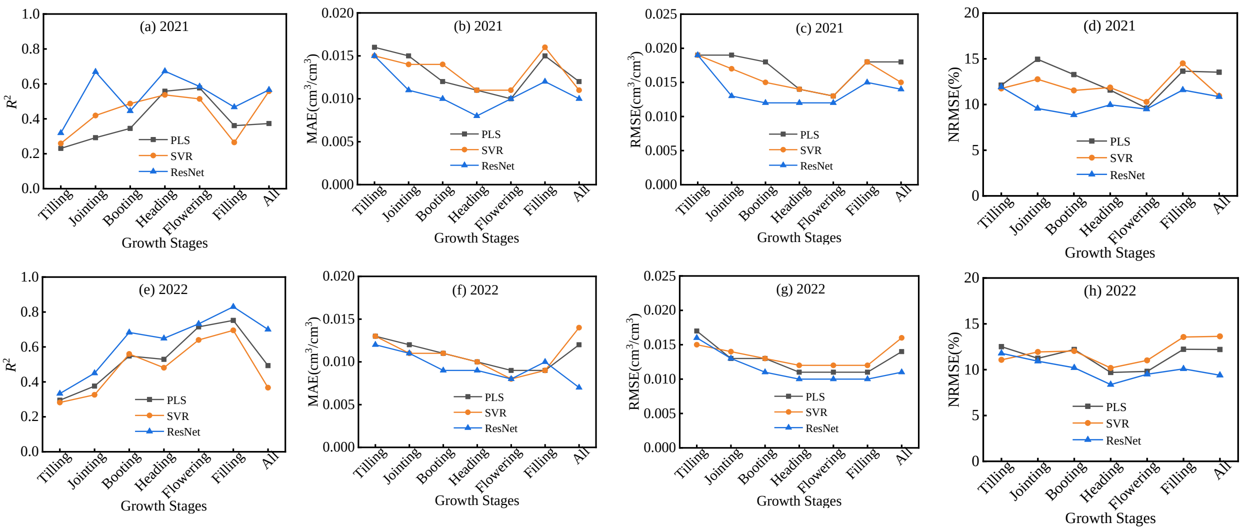


Figure 4 Result of validation set of SWC

3.4 Estimation model of CIWD

According to equation (1), combined with GS and SWC, CIWD of winter wheat was constructed, as shown in Figure 5. The effects of CIWD models constructed by different growth stages and were discriminative. In terms of different growth stages, the tillering period R^2 in 2021 and 2022 was lower, but the MAE and RMSE were also lower, so the prediction accuracy of the model was higher. Compared with the tillering stage, the R^2 of the jointing stage, booting stage and heading stage was significantly improved, but the NRMSE was not significantly improved due to the small changes in MAE and RMSE. R^2, MAE and RMSR were relatively stable at flowering and filling stages, but NRMSE had a downward trend. Compared with the single growth stage, the R^2 of the CIWD model in the muti-growth stages was at a moderate level, and the MAE, RMSE, and NRMSE were higher than those in the single growth stage, but the CIWD prediction model of the muti-growth stages constructed by the ResNet algorithm in 2021 (NRMSE of 8.608%) and 2022 (NRMSE of 9.221%) reaching an excellent level.

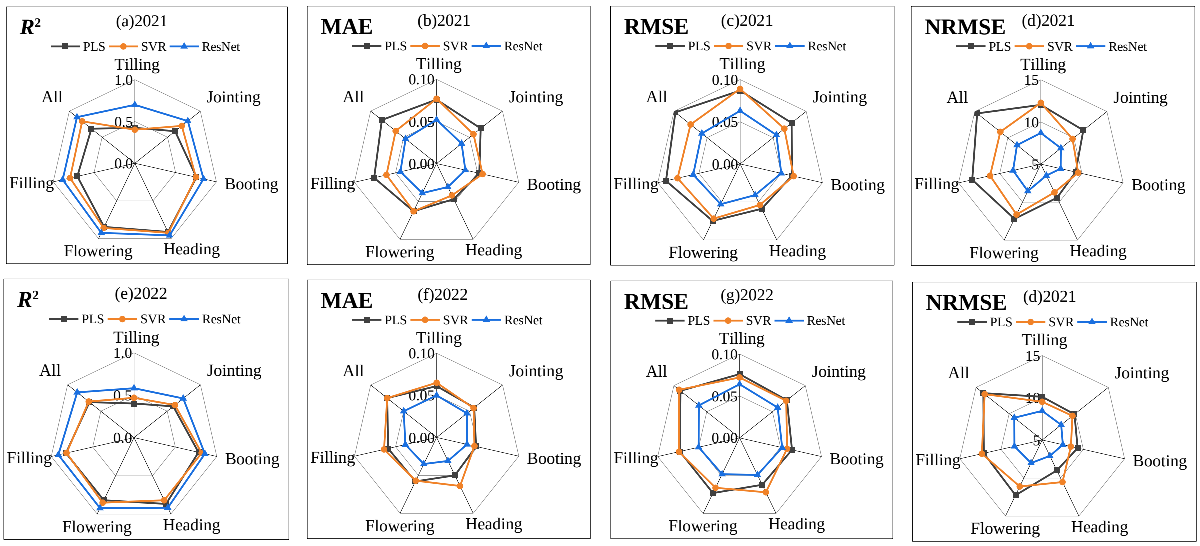


Figure 5 Results of training set of CIWD

Figure 6 showed the results of the validation set of the CIWD prediction model for muti-growth stages constructed by the three algorithms. The measured and predicted values of CIWD were evenly distributed on both sides of 1:1, which proves that the prediction of CIWD by multi-spectral remote sensing and thermal infrared remote sensing is feasible. In addition, the results of the ResNet model in 2021 (NRMSE of 9.282%) and 2022 (NRMSE of 9.545%) reached an excellent level, which shows that the use of the ResNet algorithm to predict CIWD in muti-growth stages is feasible and can provide a comprehensive Models that are common to muti-growth stages, rather than building models for each growth stage individually.

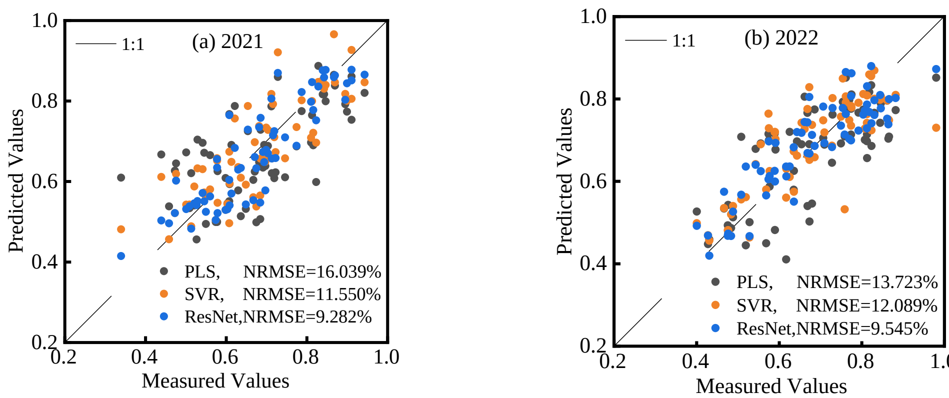


Figure 6 Results of validation set of CIWD

4. Conclusions

(1) The indices had a high correlation with Gs, SWC and CIWD, most reached a significant level (*P*<0.05), The correlations between the indices and the three indicators were GS, CIWD, SWC from big to small, and the most correlated indices were RVI and NDVI.

(2) The accuracy of CIWD models were higher than GS models and SWC models. Compared with PLS and SVM, ResNet had the best effect, the coefficient of determination (R^2) of CIWD models increased from 0.663 to 0.884 in 2021 and 0.671 to 0.852 in 2022, respectively; (iii) Among the three models, the accuracy of the CIWD models built by ResNet performed best. The models modeling R^2, mean absolute error (MAE), root mean square error (RMSE) and normalized root mean square error (NRMSE) were 0.884, 0.047, 0.058, 8.608% in 2021 and 0.856, 0.050, 0.062, 9.221% in 2022, respectively.

(3) ResNet algorithm can provide a comprehensive Models that are common to muti-growth stages, rather than building models for each growth stage individually.

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QUICK PRECIPITATING MIST SPRAYER

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ABSTRACT

The world's water resources are increasingly scarce, and human demand for food continues to rise. Traditional jetting and dropping irrigation require laying a large number of pipes, resulting in water leakage, cumbersome maintenance, affecting crop cultivation etc. The patented hydraulically driven self-propelled Quick Precipitating Mist Sprayer uses mechanical force to spray water to high altitude with clustered spray pipes, allowing the water to fall from the high altitude to the farmland accurately. Produce 'heavy rain", "moderate rain" and "light rain" on demand. At the same time, the rear hanging device can be used to complete operations such as rotary tillage, harvesting, and transportation. It is multi-functional, light, flexible, fast, and efficient. Quick Precipitating Mist Sprayer is suitable for mountains, hills, plains, plateaus, basins, and various crops. The article also describes the overall concept of low-carbon smart mechanized farms, including rational planning of farm wells, water supply systems, farm roads, and drainage channels etc., where Quick Precipitating Mist Sprayer and other agricultural machinery and equipment work together to realize higher irrigation efficiency and increase production.

Keywords: mechanical rainfall, hydraulic driven, water and energy saving, low carbon smart farm, sustainable development of agriculture

1. Introduction

The Director-General of UNESCO, Audrey Azoulay, launched the United Nations World Water Development Report at the 8th World Water Forum in 2018, she declared: "we need new solutions in managing water resources so as to meet emerging challenges to water security caused by population growth and climate change. If we do nothing, some five billion people will be living in areas with poor access to water by 2050". [1]

At the beginning of the 20th century, the appearance of high-capacity power driven pumps capable of pumping deep groundwater led to unprecedented increases in groundwater abstraction in response to ever increasing water demands. [2] The economic contribution of groundwater in agriculture has been estimated at about US$210–230 billion per year globally. [2] In the broader context, irrigated agriculture still accounts for 70% of freshwater withdrawals (FAO, 2020), and an estimated 90% of all water evaporation (Hogeveen et al., 2015). [2] In order to meet global water and agricultural demands by 2050, including an estimated 50% increase in food, feed and biofuel demand relative to 2012 levels, [2] groundwater is a critical resource for irrigated agriculture. [2]

Although China's water resources are 2.8 trillion m3, accounting for 6% of the world's total runoff resources, ranking sixth in the world [3], according to internationally recognized standards, China's fresh water resources are only 2,200 m3 per person, only 1/4 of the world's average level, ranking 121st in the world, and one of the 13 water scarce country. [4]

According to Chen Mingzhong, chairman of the National Irrigation and Drainage Commission of China, in 2019, China's agricultural water consumption was 368.23 billion m3, accounting for 61.2% of the total water consumption, and some areas even exceeded 90%. " the overall efficiency of agricultural irrigation water usage is poor, the efficient water-saving irrigation area only accounts for 30% of the total irrigation area. [5]

2. China's current status of water saving irrigation technology

China's water resource utilization coefficient is only 0.5, which is a low level in the world and far behind developed countries [6].At present, China's water saving irrigation technologies generally include: leakage free channel, accounts for 30% of the total irrigation area; low pressure pipe irrigation, accounting for 25% of the total irrigation

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area; jetting irrigation, accounting for 15% of the total irrigation area; dropping irrigation, accounting for 15% of the total irrigation area; and 15% other forms. [7]
The leakage free channel irrigation technology lay materials in the channel generally include rigid materials such as concrete, cement soil, masonry, asphalt concrete, PE, PVC, etc, it is one of the most used water saving irrigation technologies in China.

Low pressure pipe irrigation is mainly to change the channel into a pipeline, which is usually made of plastic or concrete, and its internal pressure is low, which can directly bring water resources into the farmland and avoid excessive loss of water during transportation. But if there is a problem with some pipelines, repairs are very difficult.

Leakage free channel irrigation and low pressure pipe irrigation technology reduces the loss of water from water source to farmland, but there are also problems such as reduced groundwater recharge [8], uneven irrigation, serious siltation and leakage. [9]

Traditional jetting irrigation technology includes nozzles, pipes and power equipment, etc., using a certain water pressure to spray water into the air to irrigate crops. It has a wide range of applications and can be used for large-scale irrigation. However, most traditional jetting irrigation equipment have single function only, with high energy consumption, poor irrigation uniformity, and also lack of supporting core components. [10]

Dropping irrigation technology includes drippers, pipes, head hubs and power equipment etc. It has better water saving efficiency, but higher water quality requirements, higher cost, affecting deep cultivation and maintenance is difficult. Once a problem occurs, it will have a great impact on the growth of crops, so dropping irrigation technology is not suitable for large scale crops.

Quick Precipitating Mist Sprayer has obtained international invention patents PCT/CN2014/000783, and won the Best Invention Award in the 11th China Science and Technology Innovation.

3. Quick Precipitating Mist Sprayer

The invention works like this:

The farm is planned with rational layout of water wells, water supply pipes, water supply valves, farm roads, drainage channels, etc., the water supply valve injects water into the combined water tank, then the high pressure water pump send water to sets of jet tube system, and the spiral spray pipe spray water into the air according to the set angle and height to complete rapid rainfall operation.

The rainfall can be "heavy rain", "moderate rain" and "light rain" according to the water demand of the corresponding plants, growth stages, climate, soil conditions, etc., to achieve timely, appropriate amount, precise irrigation. The spiral spray pipe has a powder spraying and smoke spraying device as well. Water and fertilizer integration irrigation and pesticides spraying can be operated, farmland transportation operations can also be carried out.

The rear of the Quick Precipitating Mist Sprayer is equipped with a machinery trailer, which can be attached to a dedicated 3-7 axis hydraulically driven rotary tiller, the speed and efficiency can reach 2-3 times that of current tractors. It can be hung with 20---56 rows of hydraulically driven rotary tillage fertilizer applicators for farmland sowing operations. The harvester can be towed to harvest potatoes, sweet potatoes, peanuts etc.

3.1 Working principle of the Quick Precipitating Mist Sprayer

Quick Precipitating Mist Sprayer relies on mechanical power to spray water with cluster type spray pipes to high altitudes, and then freely falls to the farmland after reaching a certain height to achieve rapid irrigation.

It can be equipped with 6 to18 sets of jet tube system according to different models of large, medium and small. Each set of jet tube system can spray 10-25 tons of water into the sky every hour, the width of the rainfall can be between 200 meters to 400 meters, and the spray height can reach 20 to 60 meters.

A single jet tube system supplies 10--25 tons of water per hour, and the theory result is:

Water pipe diameter(mm)	18	20	22	24	jet wind speed(m/s)
water presure (bar)	water flow(m3/h)	water flow(m3/h)	water flow(m3/h)	water flow(m3/h)	
3.00	24	27	32	38	8- 16
4.00	27	33	38	44	8- 16
5.00	33	36	42	51	8- 16

After the jet tube system is connected to the electric control valve of the spiral water spray pipe, the switch of the electric control valve is touched, the valve opens automatically, and the water enters the spiral water spray pipe. Under the pressure of the water in the pipe, the water spray from each spiral water spray pipe.1-9 spiral water spray pipes can be installed and fixed in each set of jet tube system, and can be set full water supply, two-thirds water supply, and one-third water supply to generate "heavy rain", "moderate rain" and "light rain" respectively.

The spiral water spray pipes are the core components invented by us with patented technology CN 103599859A.

For example, supposing each set of jet tube system spray 10 tons of water per hour, a machine with 10 sets, under the condition of sufficient water supply, 100 tons of water can be sprayed to the farmland per hour. With 5 tons of rain per mu, one Quick Precipitating Mist Sprayer can quickly complete irrigation of 1000 mu in 50 hours. With 5 tons of rain per mu, it can achieve irrigation depth of 8-10 cm, and with 10 tons of water per mu, it can achieve irrigation depth of 15-20 cm.

3.2 Water supply for Quick Precipitating Mist Sprayer

The water supply system is equipped with hydraulic water pumps with different flow rates according to different models, and corresponding water supply devices according to different rainfall amounts; it is reasonably equipped with 3--5 tons of water tanks. Two water supply centres can meet the irrigation water supply requirements for a 1000 mu of farmland. Well water, filtered river water or lake water can be used. Two sets of pumps send water to water supply pipe under the road of the farmland, and then the water supply valve is directly supply water to water tank of the Quick Precipitating Mist Sprayer.

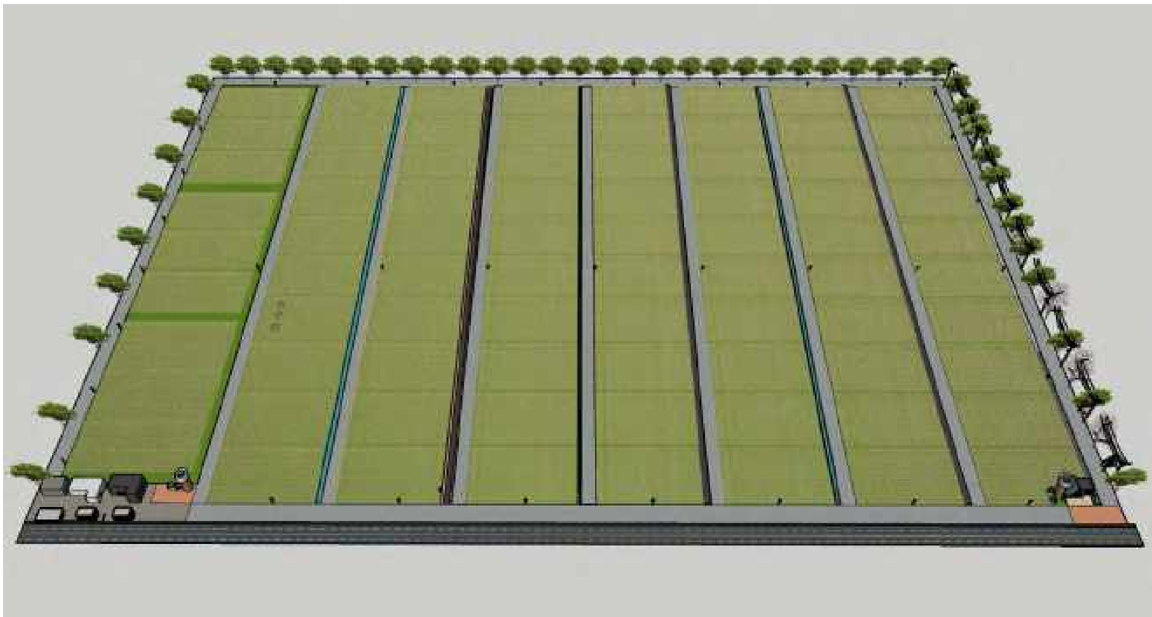
3.3 Low-carbon, energy-saving and environmental protection of Quick Precipitating Mist Sprayer

Agricultural machinery has always used tractors, to meet the needs of farm operations, tractors are equipped with more and more horsepower, more and more exhaust gas, and more and more serious environmental pollution. High-horsepower tractors naturally become oil tigers, pollution sources. Different models of Quick Precipitating Mist Sprayer are equipped with 50---250KW high-quality diesel engines, which are about 50% more fuel efficient than tractors, the emissions meet Euro 3 standards. At the same time, the core components, hydraulic pump and high-speed diesel engine deceleration connector, is also patented technology CN 103603723 B by us. This core component effectively realizes the reasonable matching between the hydraulic pump and the high speed diesel engine, and achieves the purpose of low carbon, low emission, high efficiency and energy saving.

Quick Precipitating Mist Sprayer adopts hydraulic drive, high quality diesel engine, hydraulic pump, and integrates advanced technologies such as Internet of Things system and automatic monitoring to realize the integration of multidisciplinary, multiprofessional, electromechanical, hydraulic, photoelectric and agronomic science and technology, with multiple functions, provide solution for the water resource crisis and agricultural modernization.

4. Low-carbon smart mechanized farm

China's fragmented land management are not efficiency to the development of water saving. Accelerating rural land transfers, integrating land ownership, and large-scale land management are conducive to improving water saving awareness. This is the trend of agricultural water saving technology.The low-carbon smart mechanized farm is a scientific and reasonable planning with roads, drainages, water supply centres, water supply pipes, water supply valves, trees, warehouses, solar power generation devices, water and fertilizer integration facility and soil monitors etc. Figure below indicate a low-carbon smart mechanized farm



The low-carbon smart mechanized farm is mainly composed of:

1. living area

The living area is the area for temporary grain storage and activities for the farm. In addition to the houses, there are grain storage, agricultural machinery warehouses, material storage, solar power generation devices, power supply equipment, venues and water supply centres etc.

2. water supply centre 1

Water supply centre 1 is a facility for drinking water and farmland irrigation water, preferably deep well water, or river water and reservoir water after filtration, equipped with water pumps, water towers or pressure water supply tanks or pools and main water supply pipelines for transporting water to farmland. Water for living and irrigation are supplied separately, 2 motorized wells can meet the water supply for a 1000-mu farm, which can save 90% of the cost of 1 well for 50 mu of farm invested by the country in the dry farming area of Huanghuai region.

3. farm horizontal road at the entrance

At the entrance of the farm, the horizontal road connects with the living area and two water supply centres, also connects with several longitudinal roads built for farmland operations; the main water supply pipeline is under the horizontal road.

4. farm longitudinal roads

The several longitudinal roads are built for water and fertilizer irrigation, pesticides spraying, transportation etc

5. water supply pipes under farm longitudinal roads

Under the longitudinal roads, there are water supply pipes connected to the main water supply pipeline under the horizontal road, water supply valves are spread at intervals to continuously supply water to water tank of Quick Precipitating Mist Sprayer.

6. drainage along longitudinal roads

When there is a lot of rain, the water in the farmland can be drained out of the field through this drainage, this drainage is connected to the horizontal drainage channel along the horizontal road at the end of the farm, and the horizontal drainage channel connect with the public drainage channel to discharge water.

7. farm horizontal road at the end

The horizontal road at the end of the farm is built for farm operations and connects with longitudinal roads. Fruit trees can be planted.

8. Water Supply Centre 2

Water supply centre 2 is similar to water supply centre 1, provide irrigation water to main water supply pipeline for irrigation, the difference is it has water and fertilizer integration facility, pesticide integration facility, quickly complete crops fertilization, pest control etc.

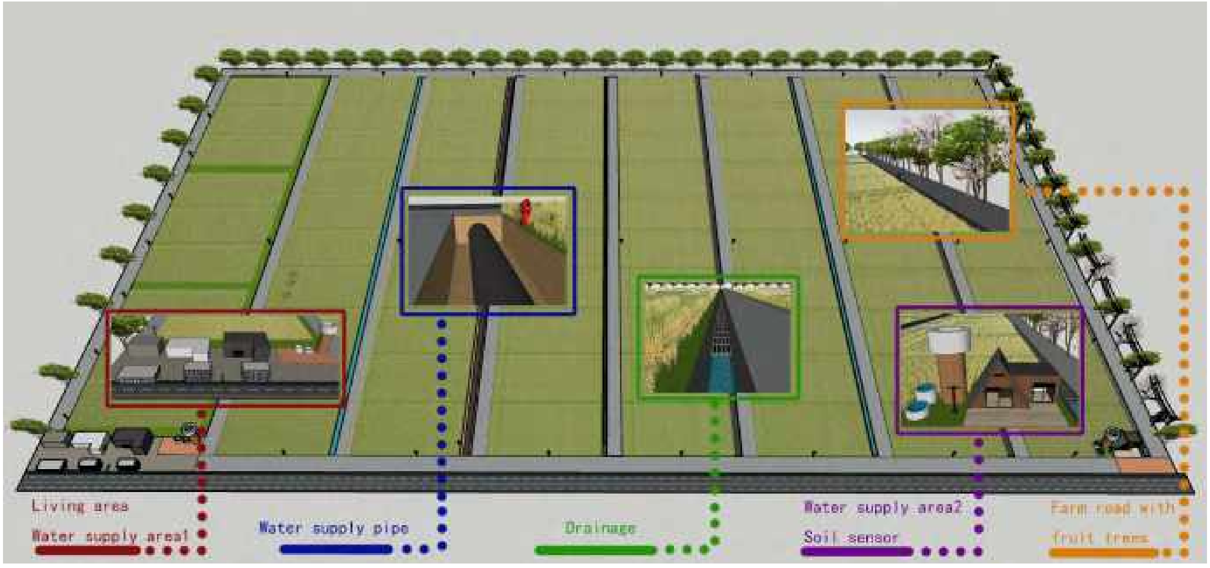
9. boundary drainages, fruit trees, electronic soil monitors, etc.

The drainages along the farm boundary are connected to discharge water, various fruit trees can be planted, several electronic soil monitors can be distributed in the farmland according to the size of the farm.

The location of the living area and water supply centres can be adjusted and the number of water supply centres can be increased according to the actual situation of the farm.

Only by actively using information technology to precisely control the speed and volume of irrigation water, actively integrating automation technology to precisely control farmland management can we achieve precise irrigation and improve the utilization of water resources.

Ideally, a 1000-mu farm, equipped with one " Quick Precipitating Mist Sprayer", one " High Speed Combined Harvesting Planting Management Machine" with patented technology PCT/CN2011/1001081, and one " 3-7 axis large hydraulic (electric) rotary tillers" with patented technology CN 102550144 B, manage by 3 skilful people, are able to realize low-carbon high efficiency mechanized operations from planting to harvesting.



5. Conclusion

The water resource crisis has seriously hindered the development of social economy, agriculture, as a large water consumer, will face the arduous task of producing more food with less water consumption now and for a long time to come. The innovative technology of the Quick Precipitating Mist Sprayer, environmentally friendly, high efficiency, energy saving, and multifunctional, can realize precise irrigation for different regions, different soils, different crops, different stages. Low carbon smart farms, improving the water saving irrigation management system, strengthening new farmers' awareness of water saving, which helps agricultural intensification, large scale operation, ensures the sustainable use of global water resources and food security.

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ADVANCES IN WATER RESEARCH: ENHANCING SUSTAINABLE WATER USE IN IRRIGATED AGRICULTURE IN SOUTH AFRICA

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ABSTRACT

Water scarcity has become one of the greatest challenges facing humankind today. Its scarcity is compounded by climate change and increasing demand from a growing population. In South Africa, over 60% of the available freshwater resources are used in agriculture, mainly in irrigated agriculture. There is an urgent need to promote sustainable irrigation technologies that optimise food production without increasing water applied and with positive environmental spinoffs. Sustainable irrigation technologies and practices could enhance water use efficiency and productivity in agriculture and reduce environmental burdens, including energy use. This review highlights some of the innovative irrigation practices and technologies that enhance food production and, at the same time, reduce water use in agriculture. The review broadly discusses water use efficiency (WUE) and water productivity (WP) in irrigated agriculture from engineering and agronomic perspectives. The review further highlights some of the environmental impacts of irrigation expansion and the possible solutions.

Keywords: Climate change; irrigated areas; water productivity; remote sensing; water security.

1. Introduction

Unsustainable overexploitation of water resources (over-withdrawn aquifers, seasonally flowing rivers, disappearing lakes and wetlands) has become one of the challenges facing humankind (Falkenmark et al., 2019). This is particularly evident in arid and semi-arid regions where water scarcity has become a real challenge threatening livelihoods and economies. Interventions that have been undertaken to minimise water scarcity in these countries include regulating water for food production, and domestic use, among other uses (Boretti and Rosa, 2019). Traditionally, these interventions have been practiced on a small scale, managed locally, and are hydrologically independent and self-regulating (Vågsholm et al., 2020). Annual rainfall, runoff, and recharge regimes would set the limits to annual use. There has been a paradigm shift in recent years due to the proliferation of large-scale storage-based systems, damming, and technological advances that have eased increased water withdrawals and created interdependence and competition across new and generally unregulated boundaries (Zeiringer et al., 2018). However, these transformations have often been accompanied by the exploitation of non-renewable resources whose governance is usually beyond the scope of local and traditional institutions.

This new norm of water governance which is compounded by increased demand has called for new innovative approaches and has witnessed the proliferation of novel concepts that promote the efficient use of water, including water productivity (WP) and water use efficiency (WUE) (Fernández et al., 2020). These innovations promote and enhance the consumption of less water, treatment of wastewater for reuse, the promotion of the circular economy in the water sector, and that whatever water is available should be used as productively as possible (Naidoo et al., 2021a; Zvimba et al., 2021). The innovations are envisaged to promote the release of more water to other uses and to achieve more production per unit of water supplied (Levidow et al., 2014).

In the case of South Africa, over 60% of the available freshwater resources are used in agriculture and mostly on 1.3 million hectares of irrigated area (Phakathi and Wale, 2018). This is happening when almost 98% of the available freshwater resources are already allocated, leaving little room for irrigation expansion (Magidi et al., 2021). Yet, agriculture is under pressure to meet the food requirements of a growing population, and the country is the thirtieth driest country in the world with an average rainfall of between 460mm to 840 mm per annum

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Figure. 1. An irrigated vineyard in the Western Cape Province. Vineyards are known for their high-water consumption if not well managed.

(Mahlalela et al., 2020). The challenge is compounded by the production of non-indigenous crops that use a substantial amount of water; these include grapes, apples, macadamia, and plums, among others (Fig. 1). Projections indicate that agricultural productivity will need to double from current production levels by 2050 to feed a projected population of about 80 million people in South Africa in the same period (Masipa, 2017). The challenges are exacerbated by climate change and scarce energy resources as rising temperatures result in increased evapotranspiration rates (Mpandeli et al., 2018). At the same time, climate change results in increasing rainfall variability, droughts, and floods, making the need to better manage water use in agriculture an urgent priority (Nhemachena et al., 2020). Given that South Africa's water resources are fully or over-allocated in most catchments, there is a need to adopt innovative irrigation technologies to enhance the sustainable use of water that allows irrigation expansion to continue to ensure water and food security.

Huge quantities of freshwater resources are already being used in irrigated agriculture, and the demand from the sector will only increase to continue producing enough food for the growing population (Magidi et al., 2021). To counter the triple challenges of water scarcity, land degradation, and food insecurity, agriculture must become more crop-water productive, efficient, and environmentally friendly. Therefore, resilience-based interventions in irrigated agriculture are multidisciplinary and inherently interdisciplinary, including specialist fields of engineering, hydrology, climatology, and geology, which should consider institutional, policy, and management issues through applied social sciences (Polasky et al., 2019). Neglecting these specialist areas during interventions will only provide partial solutions and sector efficiencies at the expense of other equally important sectors.

In South Africa, these objectives are articulated in the National Development Plan (NDP), where agriculture is highlighted as one of the key pillars to spearhead economic growth and its development is regarded as key to food security and employment creation (NDP, 2013). Agriculture remains an important sector in South Africa as it accounts for 3% of the National Gross Domestic Product (GDP) and 7% of formal employment and plays an important role in food security (Meyer and Auriacombe, 2019). The NDP (NDP, 2013) sets to stimulate economic growth in sectors like agriculture with special emphasis on irrigation expansion and employment creation (Magidi et al., 2021). The NDP emphasises improving smallholder farmers and reducing their vulnerabilities to climate change. However, there are challenges to targeted agricultural policies and investment in a dynamic environment where changes are constantly occurring, and water resources management for the agriculture sector for all-inclusive and pro-poor interventions is hotly debated (Cai et al., 2017). Although various innovations and technologies have been developed to enhance water-use efficiency, uptake has been quite low, yet these interventions are critical for comprehending water-use behaviour and devising effective institutions to manage water in times of intensifying scarcity.

2. Use and misuse of water productivity and water use efficiency terms

The terms water use efficiency (WUE) and water productivity (WP) are often used interchangeably, yet they are different altogether (Fernández et al., 2020). The use and confusion of the two terms are generally based on whether one is an agronomist or an agricultural engineer. Agronomists generally consider the WUE and WP as the same, yet in actual terms, they are distinct and, therefore, should be applied differently. Water productivity is the yield to water supplied and is expressed in weight units of yield (kg or g) to the amount of water used (m^3), for example, kg/m^3 (Molden et al., 2010; Nhamo et al., 2016). Yet, in general terms, efficiency refers to a ratio or percent, that is, the percentage or ratio of output divided by input, both with the same units (Fernández et al., 2020). For example, in irrigation, if one adds 10 mm of water to the plant and the plant consumes 8 mm through the root water system followed by transpiration and 2 mm is lost by drainage below the root zone or via bare soil evaporation from the surface. The water use efficiency here is 80%. Irrigation efficiency aims to assess the irrigation system's performance (Fernández et al., 2020). In irrigation terms, WUE is described as the ratio between the volume of water used by a crop, including the whole evapotranspiration process, and the volume that reaches the irrigated field, and is expressed as :

$$WUE = \frac{WU}{WS} \tag{1}$$

where WUE represents water use efficiency (dimensionless), WU is water that is eventually used by crops (m^3), and WS is water supplied to the irrigated field (m^3).

The difference between WUE and WP is that WP refers to the yield produced from a unit of input. There are two types of WP, physical and economic productivity (Nhamo et al., 2016). Thus, WP can be defined as the physical mass of production or the economic value of production measured against gross inflow, net inflow, depleted water, process depleted water, or available water and is expressed as (Molden et al., 2010):

$$WP = \frac{CY}{WC} \tag{2}$$

where WP represents water productivity, CY is crop yield (kg/m^3 or $\$/m^3$), and WC is the water consumed (m^3). Therefore, WUE and WP are water accounting terms essential for monitoring the efficiency with which water is supplied to the field and the rate at which the plant converts water into food, respectively. The concept of WP is critical in both rainfed and irrigated sub-sectors. It monitors and assesses water use efficiency in crop production (Parra et al., 2020). The main aim of WP is to increase crop yield per unit of water used, hence the term "more crop per drop" (Molden et al., 2010). Attaining the production of more crops with less water is possible through (i) increasing the marketable yield of the crops for each unit of water transpired, (ii) reducing water losses, or (iii) enhancing the effective use of rainfall, and the water stored in the soil (Molden et al., 2010). The first option represents the need to improve crop yield, the second aims to increase the beneficial use of water (transpiration) against the non-beneficial losses (evaporation), and the third option stands for the efficient utilisation of water resources. All these options associated with WP, coupled with modern irrigation technologies, are essential for improving on-farm crop water management practices as they facilitate the use of less water in both rainfed and irrigated systems, reduce water losses through evaporation, optimise the use of chemicals, minimise energy consumption and enhance soil conditions. These practices are important in water-scarce regions as farmers are always constrained to apply deficit irrigation strategies and to manage water supply in relation to the sensitivity of the crop's growing stages to water stress. Therefore, improved WUE catalyses WP and both improve economic return from the investments in irrigation water supply.

Table 1. Difference between water use efficiency and water productivity

Water use of efficiency WUE)	Water productivity (WP)
A dimensionless ratio of the total amount of water used to the total amount of water applied	Relationship between crop yield and water consumed
Applies to the efficiency of water used to a field	Refers mainly to the benefits from a system (rainfall or irrigated)
Refers to the performance of crops	Refers to the performance of the production system as a whole
It is an assessment of the amount of water taken up by the plant	It refers to the best returns from applied water
Does not consider losses	Loss accounted for through supply or depletion

3. Innovations enhancing water use in irrigation

3.1. Irrigation technologies

As demand for water in the agriculture sector is set to increase in the coming years amidst climate change and worsening depletion, degradation, salinisation, and scarcity, irrigation technologies are envisaged to play a critical role in ensuring water use efficiency and building a resilient irrigation sector (Nhemachena et al., 2020). However, the sustainability of irrigated agriculture depends on initiatives aimed at reducing environmental effects and the capability to maintain the adopted innovations (Vågsholm et al., 2020). Negative environmental impacts from food systems have deleterious effects in some regions (Clark et al., 2019). Food systems are one of the major contributors to greenhouse gasses (GHG) (Crippa et al., 2021). Irrigation expansion should be implemented and managed in the context of overall river basin management and regional development plans (Clarke and Crane, 2018; Mabhaudhi et al., 2018). Thus, adopting integrated approaches in irrigation planning is a prerequisite for achieving sustainability in the irrigation sub-sector (Mabhaudhi et al., 2018; Naidoo et al., 2021b; Nhamo et al., 2020).

Innovative irrigation systems and technologies enhance crop-water productivity, a pathway to producing more with lower water supplies (Levidow et al., 2014). Innovative practices in irrigation and the rest of the food system value chain are envisaged to provide an economic advantage while reducing environmental impacts such as excessive water abstraction, energy use, and pollutants (Levidow et al., 2014). The WRC and partners have developed or adapted novel technologies that enhance efficiencies in resource use in agriculture, particularly water (Table 2). Examples of such technologies include the guidelines and improved mechanisms to determine water used in irrigation and create benchmarks from which water resources management institutions and farmers can set targets to become more efficient and water productive. The guidelines and technologies are available online at www.watermeter.org.za.

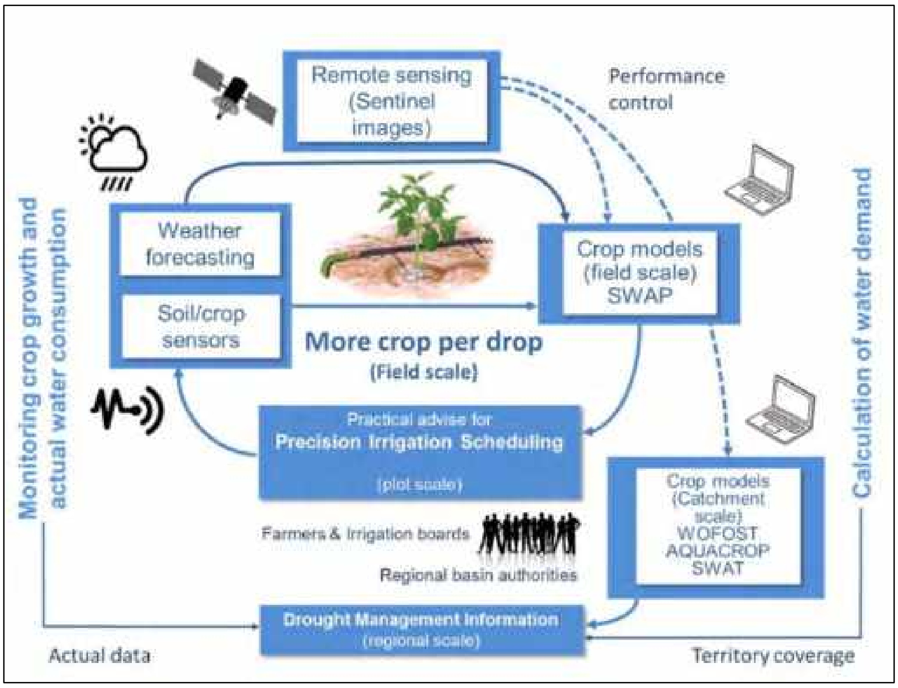
Table 2. Selected water-use efficiency innovations developed through WRC funding

Innovation title	Innovation description
Water use of drought-tolerant food crops	Crop models for underutilised indigenous crops
Improving livelihoods and scheme productivity on smallholder canal irrigation schemes	Provided insights on Chinese cabbage and green maize irrigation scheduling and three integrated crop and livestock production guidelines.
The Water use of selected fruit tree orchards	First-time use of sap flow measurements to determine transpiration of fruit trees in an orchard.
Impact of wastewater irrigation by wineries on soils, crop growth, and product quality	Contributed to the Department of Water and Sanitation's revision of the General Authorisations and supported the sustainable management of winery wastewater.
Water use of cropping systems adapted to bio-climatic regions in South Africa and suitable for biofuel production	Developed software to disseminate stream flow output from the ACRU model and assess land-use change impact on feedstock cultivation on downstream water availability.
Development of technical and financial norms and standards for drainage of irrigated lands	Developed testing and adaptation of models to determine the technical and financial feasibility of drainage in South Africa
Adaptive interventions in Agriculture to reduce the vulnerability of different farming systems to climate change in South Africa.	Developed several coping and climate change adaptation practices based on the different Agro-Ecological Zones (AEZ) and agricultural commodities.
The current rain-fed and irrigated production of food crops and its potential to meet the year-round nutritional requirements of rural poor	Providing new knowledge about water harvesting practices and systems for the delivery of water to gardens to reduce drudgery for women are essential to enable food production in more homes

3.2. Smart Water Management

Smart water management in agriculture is defined as using information and communication technology (ICT) and (near) real-time data and responses to measure, control, and distribute agricultural water to save water and energy. The WRC has developed such innovations through its funded research, as in Table 2. Spatial and temporal agricultural water management (Fig. 2) is critical in irrigated agriculture, wherein challenges of agricultural water mismanagement and scarcity persist and undermine livelihoods that mainly depend on irrigated agriculture.

Innovative smart water management technologies have been developed, including a model to estimate crop evapotranspiration, yield, and water-use efficiency in sub-basin for small grains such as soybean and sorghum. The model is essential for rural farming communities as it guides the best agronomic practices to maximise attainable yield. Another WRC-funded project developed an operationalisation model to increase water use efficiency and resilience in irrigation (OPERA), a technology that allows direct mapping of soil water (as done with in-situ observations, air- or space-borne radar), crop water stress by thermal infrared sensors and modelling of the crop/soil/atmosphere continuum. When adequately fused with terrestrial measurements, these mapping tools offer decision support for improved agricultural water management.



Figuer. 2. Linking weather, remote sensing, in-situ crop and soil sensors, crop and soil models, and stakeholders to synthesise case study results in a concept for an operational support of precision irrigation (OPERA) system at field scale and water saving at catchment scale

To counter salinity challenges, an innovative decision support system (DSS) has been developed to manage irrigation-induced salinity with precision agriculture. A related study developed an integrated bioeconomic model to economically manage site-specific water and salt stress in irrigated agriculture. This was achieved by linking the transient state soil-water-crop model (SWAMP) to an economic model and an optimisation procedure to evaluate site-specific water and salinity management.

4. Potential environmental impacts of irrigation development

Besides the many benefits of irrigation and its expansion, many trade-offs accompany its development, including increased soil degradation and erosion; pollution of both surface and groundwater; degradation of water quality; increased eutrophication due to high nutrient levels in the irrigation and drainage water resulting in algal blooms in irrigation canals and downstream waterways (Malakar et al., 2019). Irrigation projects that impound or divert river water may cause environmental disturbances and can be a health risk due to hydrology and limnology changes in river basins (Kibret et al., 2021). Alterations in river flow regimes can potentially result in salt water intrusion in river systems and into the groundwater of nearby agricultural lands (Richter and Thomas, 2007). If not well planned, river diversion to irrigated lands reduces the water supply for downstream users. Some of the environmental impacts and possible solutions are shown in Table 3.

Table 3. Environmental impacts of irrigation development and practical solutions

Environmental impacts	Mitigatory solutions
Waterlogging and salinization	Situating irrigated lands where negative impacts are minimal
Changes and alterations to ecosystem services	Restoring degraded irrigated lands rather than establishing new ones
Water-borne and water-related diseases	Improving the efficiency of existing irrigation schemes
Destruction of natural habitats	Recycle wastewater for use in irrigation

6. Conclusions

Irrigation remains vital to ensure the continued provision of food and water resources in the advent of climate change and increasing depletion and degradation. The role of irrigated agriculture in enhancing crop production, water-use efficiency, and water productivity remains indisputable. Various agronomic, engineering, and water management innovations have recently been developed to reduce water losses in irrigated agriculture. This is mainly based on the fact that irrigated agriculture is recognised by the CAADP and the Southern Africa Development Community's (SADC) Regional Agriculture Policy (RAP) and South Africa's Agricultural Policy and the Strategic Plan, as a sustainable climate adaptation strategy. Therefore, the call to increase irrigated agriculture in Africa has been very much pronounced as agriculture is the backbone of many African economies. Whilst increasing the land under irrigation is a prerequisite to enhancing food and water security, policy should adopt holistic and integrated approaches when implementing irrigation strategies to avoid policy spillovers or attain unintended outcomes. Innovations that promote water use efficiencies are critical for the resilience and adaptation of the agriculture sector that it continues to provide the food requirements of an increasing population. However, the uptake of innovative technologies in the sectors has been very slow. While acknowledging the importance of innovative technologies for the sustainability of irrigation, it is equally critical to recognise trade-offs and synergies associated with irrigation expansion. This knowledge brings the importance of transformative and holistic approaches to irrigation expansion and development. The fundamental questions that need to be addressed include the availability of water and energy resources in the case of South Africa and other water-scarce countries.

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AN INTEGRATED APPROACH AND THE FACTORS REQUIRED IN IRRIGATION SUITABILITY MAPPING

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ABSTRACT

Most emerging economies are reliant on agriculture, yet over 90% of the sector remains rainfed. However, as rainfed agriculture is highly susceptible to climate change, agriculture has been struggling to meet the food requirements of an increasing population. The challenges of low productivity in rainfed systems are prompting a shift towards a more efficient crop-water productivity system of irrigated agriculture. This study integrated geospatial processes and the multi-criteria decision method (MCDM) to delineate irrigation suitability areas, applying physical factors that include slope, rainfall, landuse, closeness to waterbodies, soil characteristics, and groundwater depth. The selected physical factors were classified into four suitability classes (S1, S2, S3, and N) proposed by the Food and Agricultural Organization (FAO). Irrigation suitability areas were then delineated by initially weighting the factors through the Analytic Hierarchy Process (AHP), a MCDM, and combining the layers using the weighted overlay tool in ArcGIS. Socio-economic factors were excluded in this instance as they are only ideal for identifying priority areas to initiate irrigation projects under a set of given conditions. As hydrologic factors were weighted the highest, optimal irrigation suitability areas are shaped by their closeness to water sources, be it surface or groundwater.

Keywords: Land suitability; multi-criteria decision; agricultural water management; adaptation; water security

1. Introduction

Land, together with water and energy, are important resources that drive economies, and their sustainable management promotes resource security, and socio-economic and ecological sustainability (Lambin and Meyfroidt, 2011; Nhamo et al., 2022). In particular, the quality of land is often defined by agricultural development and how it contributes to food and water security (Viana et al., 2022). In this context, sustainable agricultural production plays a pivotal role in formulating agricultural and rural development policies (Nhamo et al., 2022). However, the pressure on land resources continues to mount due to population increase, degradation and erosion, and climate change. As land is a key resource, its allocation and distribution are generally influenced by the need to meet socio-economic and food security needs (Nhamo et al., 2022). The close interlinkages between socio-economic development, available natural resources and the policies that guide the use of these resources are, therefore, quite evident in land planning (Gebre and Gebremedhin, 2019).

The increasing pressure being exerted on land resources from both the growing population and the competition emanating from different land uses requires integrated, efficient and sustainable land use management practices. Sustainable land use management is a guarantor of resource security for both the present and future generations, yet current unsustainable land management practices lead to irreversible consequences (Lampert, 2019). The recognition of land degradation amidst the increasing population, worsening climate change, and dwindling food resources, among other challenges, are the main reason for the calls to increase the area under irrigation, and the formulation of governance frameworks on irrigation expansion including the 2030 Sustainable Development Goals (SDGs) (Magidi et al., 2021b).

There are, therefore, broad interlinkages between land, agricultural development, water-use efficiency and food security (Viana et al., 2022). Thus, efficient agricultural water management is key to improving crop-water productivity, providing pathways towards water and food security and enhancing climate change resilience (Nhemachena et al., 2020). On the other hand, a sustainable agricultural system promotes both rural and economic development and catalyses environmental and human health (Vågsholm et al., 2020). However, sustainable agriculture has been evasive, particularly in developing countries where agriculture remains rainfed under traditional methods that are generally environmentally unsustainable (Ahsan et al., 2021). The challenges

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are compounded by the observed late onset of rains, resulting in shortened growing seasons, prolonged intra-seasonal drought spells, and higher intensity rains that cause floods (Mpandeli et al., 2019). Without adaptation strategies in place, there have been noted reductions in the quantity and quality of crop yields, coupled with crop damage, and even loss of entire harvests and livestock mortality (Nhamo et al., 2019; Serote et al., 2021). With the increasing demand for water and food resources, agro-food systems need to produce more with less water and, at the same time, meet the rising food demand (Uhlenbrook et al., 2022).

Irrigation is being promoted as key to increasing crop productivity, enhancing water use efficiency and catalysing agricultural sustainability and economic development (Uhlenbrook et al., 2022). In Africa, in particular, where the economies of most countries' Gross Domestic Product (GDP) are reliant on agriculture, the call is even more pronounced (AU, 2014). Moreover, irrigation is an indispensable climate change adaptation strategy, particularly for smallholder farmers who contribute over 90% of the agricultural produce in sub-Saharan Africa (SSA) (Magidi et al., 2021a). Based on these challenges, and the need to boost African economies, the African Union (AU) and regional economic blocs have prioritised increasing the area under irrigation as a means of promoting the resilience and sustainability of agriculture (AU, 2014; NEPAD, 2003).

This study adopted an integrated geospatial-based and multi-criteria decision method (MCDM) procedure for irrigation suitability mapping in Masvingo District, a semi-arid area in the south-east of Zimbabwe. The aim was to provide more accurate irrigation statistics for strategic policy formulations and guide irrigation development as current methods are varied and developed at varying coarse spatial resolutions (Cai et al., 2017; Magidi et al., 2021a; Massari et al., 2021). Accurate spatial information on irrigation suitability, distribution and extent is a prerequisite for coherent and strategic policy decisions on irrigation development, design, and implementation. As there has been no consensus on the factors to consider in irrigation suitability mapping, this study also defines the most appropriate factors for irrigation suitability mapping.

2. Methodology

The delineation of irrigation suitability areas was processed in ArcGIS Spatial Analyst's Weighted Overlay tool, which is based on the MCDM method. The input layers were created, classified and weighted to determine irrigation suitability areas using the Analytic Hierarchy Process (AHP). The weights for each of the factors were determined through the pairwise comparison matrix PCM of the AHP (Hagos et al., 2022; Saaty, 1977). The irrigation suitability criteria (also known as factors) include slope, rainfall, soil texture, soil drainage, soil depth, closeness to water source (both surface and groundwater), and land use/land cover (Hagos et al., 2022; USDIBR, 2005). These biophysical factors are key in irrigation suitability mapping in any given landscape (USDIBR, 2005). Socio-economic factors that include population density, closeness to markets and proximity to roads are excluded at this stage as they are useful for identifying priority areas for implementing irrigation projects under a set of given socio-economic conditions (USDIBR, 2005). Economic factors are applied to already identified irrigation suitability areas.

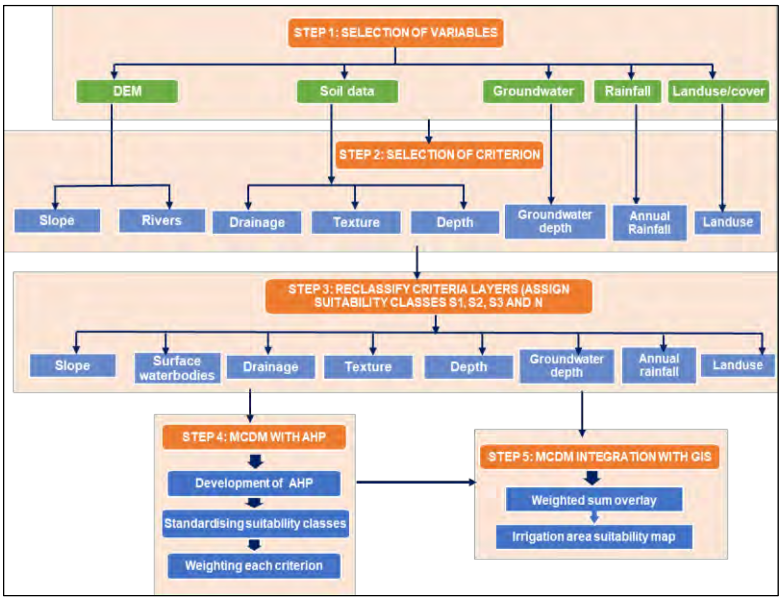

Figure. 1. Overall conceptual flowchart to delineate areas suitable for irrigation

Population density, closeness to markets, transport networks, or other socio-economic factors do not determine whether an area is suitable for irrigation but are applicable for identifying priority areas for implementing irrigation projects (USDIBR, 2005). Therefore, socio-economic factors are only essential during the second phase which is informing policy and decision-makers on optimal areas for immediate irrigation development but do not determine an area's suitability for irrigation (USDIBR, 2005).

The overall modelling flowchart (Fig. 1) provides a stepwise process followed to delineate irrigation suitability areas, a procedure that is replicable at any spatial scale. The framework has five main steps that are followed to produce an irrigation suitability map. The first step involves the selection of the variables needed to classify the land into irrigation suitability areas and the preparation of input data layers. The input data layers for preparation included the digital elevation model (DEM), soil data, surface water and landuse/cover datasets. The second step consists of the selection of the criteria from the variables and data cleaning and pre-processing, including converting the input data layers into a uniform spatial resolution.

The third step involves the reclassification of criteria layers and assigning suitability classes according to the FAO classification criteria. The fourth step consists of applying the Analytic Hierarchy Process (AHP) in a multi-criteria decision method (MCDM). This includes the application of the pairwise comparison matrix (PCM) and the weighting of the criteria as each criterion is given a unique weight. The weighting of input layers is based on that each layer influences differently on irrigation suitability. Lastly, the fifth step involves integrating the MCDM with Geographic Information System (GIS) with the ultimate output of an irrigation suitability map.

2.1. Data collection and sources

The fundamental task to achieve the objective is to access and prepare the various datasets needed for input and resample them to a uniform spatial resolution (Table 1). The datasets were obtained from the Soil and Terrain (SOTER) Digital Database (for soil factors), the British Geological Survey (BGS) (from where the groundwater depth in mbgl was downloaded), ASTER GDEM (from where slope in degrees and river systems where derived), Sentinel (for the classification of landuse/cover layer) and the Food and Agriculture Organisation (FAO) (where the rainfall dataset was downloaded. Following the collection of data, additional analysis like the reclassification of layers and their weighting was conducted.

Table 1. Data sources resolution and derived layers

Data type	Data format	Spatial resolution	Source	Derived layers
Soil map	Vector	1:250 000	AfriGIS	Soil texture, drainage and depth
DEM	Raster	30 m	Aster GDEM	Slope and altitude
Rainfall	Raster	5km	FAO	Annual rainfall
Groundwater	Raster	5km	BGS	Groundwater depth
Landuse/cover	Raster	30 m	Sentinel	Landuse/cover
Surface waterbodies	Vector	1.50 000	FAO	Waterbodies

2.2. Categorising the irrigated area suitability mapping factors

Table 2 provides the sub-factors, and the suitability classes assigned to each of the factors. The factor layers are reclassified in ArcGIS according to the respective ratings and are assigned weights developed through the PCM.

Table 2. Irrigated area suitability mapping factor classifications

Factors	**Sub-factor**	**Factor classifications**				**Source**
		S1	**S2**	**S3**	**N**	
Topographic	Slope (%)	0-2	2-5	5-8	>8	(Mandal et al., 2018)
Climatic	Av. annual rainfall (mm)	>800	600–800	600–400	<400	(FAO, 1976)
Edaphic	Drainage class	Well	Moderately well	Imperfectly	Poor	(Mandal et al., 2018)
	Depth (cm)	>100 (Very	50–100 (Moderately	10–50 (Shallow	<10 (Very	(Nachtergaele et al., 2010)

Factors	Sub-factor	Factor classifications				Source
		deep)	deep)	)	shallow	
	Texture	L–SiCL, C	SiL, SCL, CL	SL	LS, Si–L	
Hydrologic	Groundwater depth (mbgl)	<50	50–75	76–100	>100	(MacDonald et al., 2012)
	Distance from rivers (m)	0—721	721—1442	1442—2163		(Hagos et al., 2022)
Landuse	LU/LC	Cropland	Grassland	Barren & shrubland	Constraints (Forest, built-up, water, wetland)	(Yohannes and Soromessa, 2018)

3. Results and discussion

As the criteria or layers (as they are known in GIS) are not equal in importance, they are compared or differentiated from each other through weights. The weights are determined through expert opinion and literature search and are ranked according to their importance to irrigation suitability mapping by applying the PCM (Table 3). The weights are then used as input data to the layers in ArcGIS using Saaty's AHP pairwise comparisons scale (Saaty, 1987; Saaty, 1977).

Table 3. Pairwise comparison matrix for assessing the relative relevance of eight factors

	Dist. from rivers	Groundwater depth	Soil depth	Slope	Soil texture	Drainage class	LU/LC	Rainfall	Average weights	Weights (%)
Dist. from rivers	1	0.5	0.33	0.25	0.2	0.17	0.14	0.12	0.331	33.1
Groundwater depth	0.5	1	0.5	0.33	0.25	0.2	0.17	0.14	0.231	23.1
Soil depth	0.33	0.5	1	0.5	0.33	0.25	0.2	0.17	0.157	15.7
Slope	0.25	0.33	0.5	1	0.5	0.33	0.25	0.2	0.106	10.6
Soil texture	0.2	0.25	0.33	0.5	1	0.5	0.33	0.25	0.071	7.1
Drainage class	0.17	0.2	0.25	0.33	0.5	1	0.5	0.33	0.048	4.8
LU/LC	0.14	0.17	0.2	0.25	0.33	0.5	1	0.5	0.033	3.3
Rainfall	0.12	0.14	0.17	0.2	0.25	0.33	0.5	1	0.024	2.4
CR = 2.9% (0.029)										

The PCM is essential for weighting the irrigation suitability mapping factors, comparing them one-to-one according to Saaty's scale (Saaty, 1977). The reliability and integrity of the comparison matrix are evaluated using the consistency ratio, calculated at 0.029, which is within the acceptable range.

The distance from surface water sources and groundwater depth are weighted the highest (Table 3) as the ease of access to water sources (rivers, dams and groundwater) is fundamental to irrigation development, and reduces the abstraction and pumping costs from the water source to the field. Adequate water supply and availability are at the centre of a successful irrigation system (Levidow et al., 2014). Proximity to groundwater is ranked as the second highest factor as it is slowly becoming the main water source for irrigation during the dry season or intra-seasonal dry periods as surface waterbodies continue to deplete or degrade (Cai et al., 2017; Magidi et al., 2021a). Although both surface and groundwater sources are key for irrigation development, groundwater has been placed in the second position after surface water (Table 4) as it is more expensive to abstract compared to pumping from surface waterbodies. Where surface water is readily available in sufficient quantities, it may not be necessary to abstract groundwater resources (Carrard et al., 2019).

As already alluded to, soil depth is key as it provides root anchorage and accessibility to water and crop nutrients, crucial factors that promote and favour increased agricultural production, and therefore is ranked third. On fourth ranking is the slope factor which determines the type of irrigation practiced in an area (Hagos et al., 2022; Worqlul et al., 2017). Irrigation is preferred in low slopes to flat areas, while steep slopes are considered unsuitable for irrigation (Hagos et al., 2022). Other edaphic factors like soil texture and drainage class are ranked fifth and sixth, respectively, as they play an important role in plant growth, aeration, and water holding capacity (Hagos et al., 2022). The landuse/cover and rainfall factors are ranked seventh and eighth, respectively. The landuse/cover factor is important for discarding unsuitable areas (built-up areas, nature and game reserves, etc.) and at the same time optimising the most suitable areas like cultivated lands.

Rainfall is the least ranked factor as irrigation is only applied where rainfall is absent for prolonged periods to support plant growth, which is during the dry seasons, drought, or intra-seasonal dry periods. However, rainfall is needed to recharge both surface and groundwater sources. Weights are, therefore, assigned according to a factor's characteristics and its relationship and importance to irrigation suitability.

3.1. Irrigation suitability area

The irrigation suitability map of Masvingo (Fig. 3) indicates that optimal irrigation suitability areas are shaped by their closeness to water sources, be they surface or groundwater. This is based on that hydrologic factors were given the highest weights, thus, have the greatest influence in determining irrigation suitability. The further an area is from waterbodies, the greater the possibility of becoming unsuitable for irrigation as the other factors were weighted less, as well as the influence of constraints depicted as not suitable (N) in input layers. Being a dry area, the distribution of irrigation suitability area around waterbodies and the proportion of the unsuitable area (67.8%) to the total land area becomes logical (Table 5). The irrigation suitability areas (22.2%) are mainly around the perennial rivers and dams.

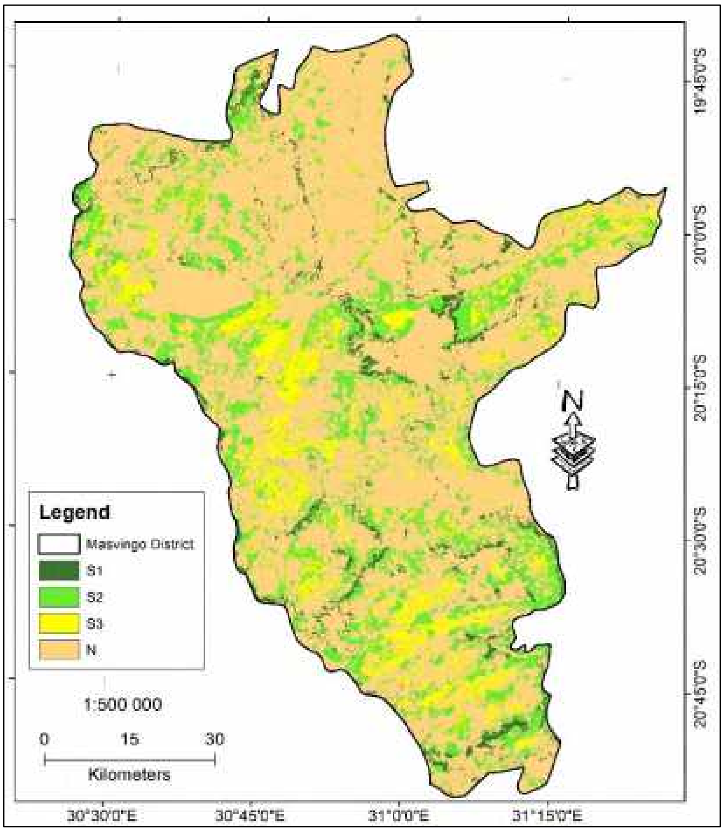

Figure 2. Irrigation suitability areas in Masvingo Districts

The substantial proportion of unsuitable areas for irrigation in the district is based on that it lies in the driest agro-ecological region of the country, a region with many agricultural constraints. Therefore, due to the dry conditions, the district has a small density of perennial river networks. Due to the harsh climatic conditions and limited annual rainfall, groundwater resources are found to be quite deep, making them difficult to be exploited for irrigation, as there is not much groundwater recharge. The harsh climate conditions and constrained agricultural conditions in the district contribute to limited commercial farming Therefore, the district is predominantly a smallholder farming area under rainfed agriculture.

The land area that is classified as moderately and marginally suitable can further be improved by adopting modern land management practices and applying the most suitable irrigation types and technologies. Irrigation suitability assessment using GIS facilitates measuring and evaluating of long-term impacts of land suitability analysis on land productivity. The parameters applied for irrigation suitability evaluation were entirely physical, factors that are essential for determining or delineating irrigation suitability areas.

The overall spatial suitability assessment for irrigation in Masvingo District indicates that 37% of the study area is potentially suitable for irrigation. Of the potentially suitable land, 6% is highly suitable (S1), 22% is moderately suitable (S2), and 9% is classified as marginally suitable (S3) (Table 4). More than half of the land of the district (63%) is constrained for irrigation.

Table 4. Area by irrigation suitability classification category in Masvingo Districts

Class	Area (Ha)	Percentage (%)
S1	25 593.39	3.71
S2	135 564.66	19.64
S3	60 749.02	8.80
N	468 442.73	67.86
Total	690 349.81	100

4. Recommendations

As irrigation is an important climate change adaptation strategy, accurate statistics on its distribution and extent are vital for irrigation planning and development. However, if the planning and development are not based on accurate information, irrigation could become one of the most disturbing anthropogenic interventions in the terrestrial water cycle (Magidi et al., 2021b). Knowledge of the distribution and extent of irrigated areas, together with the amount of water used in irrigation, plays an important role in modelling irrigation water requirements and allocation, and also quantifies the impact of irrigation on regional climate, river discharge, and groundwater depletion (Borsato et al., 2020). Therefore, delineating accurate irrigation suitability areas improves decisions on irrigation development and expansion and promotes food and water security initiatives in an era of climate change. Equally important in irrigation suitability mapping is the selection of the appropriate factors. It is essential to understand the role of each of both physical and socio-economic factors in irrigation suitability mapping. Irrigation investment is identified as key to enhancing and maintaining sustainable food security as it improves agricultural production, which is the foundation for southern Africa's economic growth, food security, and sustainable development. Sustainable irrigation development and policies in the region should consider the following to achieve the intended objectives:

- The actual implementation of irrigation projects needs to acknowledge the interlinkages between suitability constraints that include water quality, human and environmental health, and economic and social factors with sustainable development.
- Advances in GIS and remote sensing facilitate systematic land suitability assessment over time, as well as the delineation of updated land use and irrigation land suitability for sustainable resource planning and management. Therefore, GIS and remote sensing are important tools to generate more accurate and high-resolution input datasets.
- Policy-makers should be aware that accurate spatial information on irrigation statistics is not only important for irrigation development, management, and planning but is also beneficial for economic growth and for informing future needs including meeting future land, water, and food demands.

5. Conclusions

Irrigation suitability classification is important for landuse planning according to its agricultural potential and is required for conserving natural resources to meet the needs of future generations. Thus, this study is informed by the knowledge that classifying land suitability for sustainable use requires an understanding and the selection of the correct land characteristics of the suitability theme being studied. The study used physical factors as input layers and adopted a geospatial and multi-criteria decision method approach to delineate irrigation suitability areas. The approach distinguished biophysical and socio-economic factors as the two sets of factors contribute differently to land suitability mapping. Physical factors identify areas suitable for irrigation in space and time, yet socioeconomic factors guide policy to identify optimal irrigation suitability areas to initiate irrigation projects under a set of given socio-economic conditions. The distinction between physical and socioeconomic factors has improved irrigation suitability mapping as previous studies combined both factors for general irrigation suitability mapping, thereby eliminating other suitability areas. The approach is applicable at any spatial scale, however, the availability of datasets at an acceptable spatial resolution remains a major challenge. The essence of irrigation suitability mapping is its support for policy and decision-making on strategic and sustainable irrigation planning and development. The adopted approach and the results are essential for designing and initiating new irrigation projects by providing policy with a technique that can reliably inform future irrigation development.

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DESIGN AND IMPLEMENTATION OF INTELLIGENT FLAT GATE SYSTEM OF OPEN CHANNEL BASED ON PROGRAMMABLE LOGIC CONTROLLER AND INTERNET OF THINGS

Jiang Mingliang[1]

ABSTRACT

The intensive and efficient utilization of water resources is important in the modernization of irrigation districts in China. As a universal hydraulic structure, the sluice plays an important role in the allocation of water resources in irrigation districts. In order to realize intelligent control of water transmission and distribution in irrigation channel, this study adopted the sensor measurement, electrical control, mechanical design and manufacturing and wireless communication technology, developed an intelligent channel system of flat gate based on Programmable Logic Controller (PLC) and the Internet of things, the system mainly includes two parts: remote monitoring system of in situ gate terminal and the Internet of things. Using the basic method of open channel flow measurement theory, combined with information sensing technology, the gate system has the metering function of channel water level, gate opening, gate flow and other parameters. Symmetrical double rack and pinion was used as the driving mechanism of gate lifting, which improves the stability, safety and efficiency of gate opening and closing operation. The local gate terminal control device based on PLC was developed, which has the functions of automatic control and wireless communication. The gate remote monitoring platform software based on Internet of Things technology has been developed, including mobile phone terminal and computer terminal, realizing the remote monitoring and information data management of the gate. Test results showed that the gate terminal performance is stable, the system has high measurement accuracy, convenient operation and maintenance. The maximum error of gate opening control is 1 mm, network packet loss rate close to zero, free from flow measurement error is less than 4.6%, and the flood discharge is less than 8.3%.

Keywords: Open channel; Flow measurement; Flat gate; Remote intelligent control; Internet of Things

1. Introduction

Water-saving irrigation plays an important role in improving agricultural planting efficiency and rural ecological environment. By the end of 2020, China's water-saving irrigation area reached 3.78×10^5 km^2. In the past 30 years, the average annual water consumption for agricultural irrigation in China has accounted for about 56% of the total social water consumption, and the total agricultural water consumption in China has been basically stable. As a major public welfare infrastructure, irrigated district is an important support for China's economic and social water security and agricultural and rural development.

The grain yield per unit area of large and medium-sized irrigation districts is higher than the national average. According to statistics, the grain produced in large and medium-sized irrigation districts accounts for about 50% of the national total. The modernization of irrigation districts is an important starting point to promote the rural revitalization strategy. In the past 10 years, the development of irrigation and water conservancy in China, especially the implementation of supporting facilities and water-saving renovation projects in large and medium-sized irrigation districts, has made a great contribution to ensuring national food security and promoting the healthy development of agricultural economy (Chen et al.).

It can be seen that irrigation district plays an important strategic role in China's agricultural production. But, at present our country farmland water conservancy still faces many shortcomings and problem. For example, in large irrigation districts, branch canals and branch drains are still aging and disrepair problems, and the installation rate of lateral canal measuring facilities is not high.

Channel irrigation is one of the irrigation methods widely used at present because of its low cost and convenient management. As a basic water conservancy engineering facility, channel gate plays an important role in water control and allocation in modern irrigation areas. Agriculture in the irrigation canal system in the developed countries abroad intelligent water transmission and distribution research started earlier, also emerged one batch of mature technology, researchers in Australia, the United States, Israel and other countries generally water

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transmission and distribution process of computer communication technology is used to control systems, so as to realize the efficiency of irrigation water resources allocation, rationalization, " Total Channel Control " (TCC) from Rubicon was introduced to mount Cambridge Irrigation District in the United States.

The average loss of the Cambridge channel overflow was reduced to 0.009 m^3/s in 2020, this precise management has resulted in water savings, which in turn have provided significant crop yield benefits and improved watershed water sustainability. After the introduction and application of the TCC in the east main canal of the Second dam of Fenhe River Irrigation area in Shanxi Province of China, the abandoned water can be effectively reduced and the water-saving effect is more than 20%(Guo et al.), But its introduction cost is high. After more than 20 years of construction and renovation, the problems of disease risk and leakage of backbone canal system in large and medium-sized irrigation districts in China have been basically solved.

At present, the gate configuration of main canal and branch canal in irrigation districts in China is relatively perfect, and the automation level of water metering facilities has been improved. However, the sluice gate allocation rate of ditches and agricultural canals is still low, and the traditional sluice gate is still used in most water conveyance systems, and the flow measurement method is extensive. Moreover, the intelligent level and measurement accuracy of the gate are poor, and the discrete manual operation and open-loop control of the gate are still the main (Shi, Bao et al.), which seriously affects the scientific distribution of water resources in the field, and there is still a big gap with the information construction and modernization construction of irrigated areas.

Carrying out water measurement in irrigation districts is an effective way to save agricultural water resources and improve farmland irrigation efficiency. At present, China's water conservancy industry is vigorously implementing large-scale irrigation district reconstruction projects, and actively promoting the comprehensive reform of agricultural water price. Among them, there is a great demand for high-precision and high-stability water metering equipment. This research was oriented to the needs of informatization and automation of water transmission and distribution in small and medium-sized irrigation channels in China, based on the theory of open channel flow, the sensor measurement, electrical control, mechanical design and manufacturing, such as wireless communication technology, developed a flat gate based on PLC and the Internet of things intelligent channel system, with functions of measurement and control one of the characteristics, The purpose is to realize the remote intelligent measurement and control of the local gate terminal, promote the precision, high efficiency and information control of the water delivery in the irrigation area, and improve the utilization efficiency and benefit of agricultural water resources.

2. Gate flow measurement principle and system composition

2.1 Flow measurement principle of rectangular flat gate

The theoretical basis of this study is the principle and method of flow measurement in open channe (Zhang et al.). The flat gate of rectangular open channel can adjust the flow through controlling the opening of the gate. The main advantages of flat gate of rectangular open channel are low energy consumption, small occupation area and easy installation, which make it suitable for use in most irrigation areas. The sluice outlet state of the flat gate of open channel includes sluice outlet and weir flow, among which sluice outlet can be divided into free outlet and submerged outlet (as shown in Fig. 1).

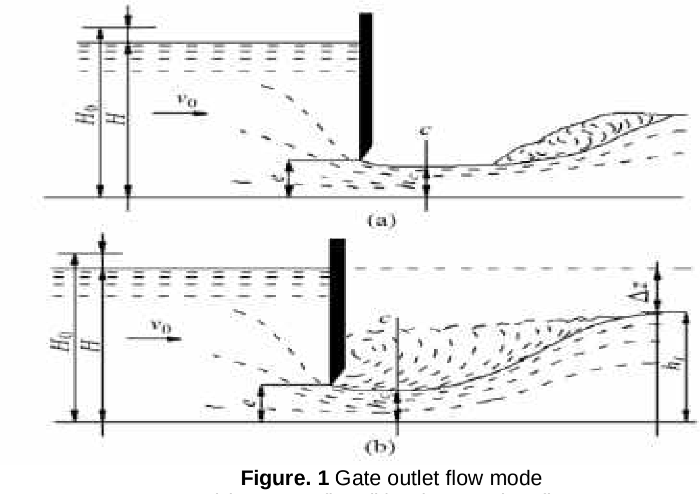


Figure. 1 Gate outlet flow mode
(a) Free outflow (b) submerged outflow

When using flat gate of rectangular open channel to measure flow, different flow formulas should be used according to different flow modes. According to the installation and use conditions of the gate, the flow state through the gate shall be determined according to the flow chart shown in Fig. 2(Zhang, Xia, and Jiang et al.). In addition, the upstream water level of the gate *H*, the downstream water level of the gate h_t, gate opening *e* and other three parameters can be measured by the sensor instrument. In practical application, moving water level is usually ignored and *H* is used to replace the total head H_0 in front of the gate containing water kinetic energy.

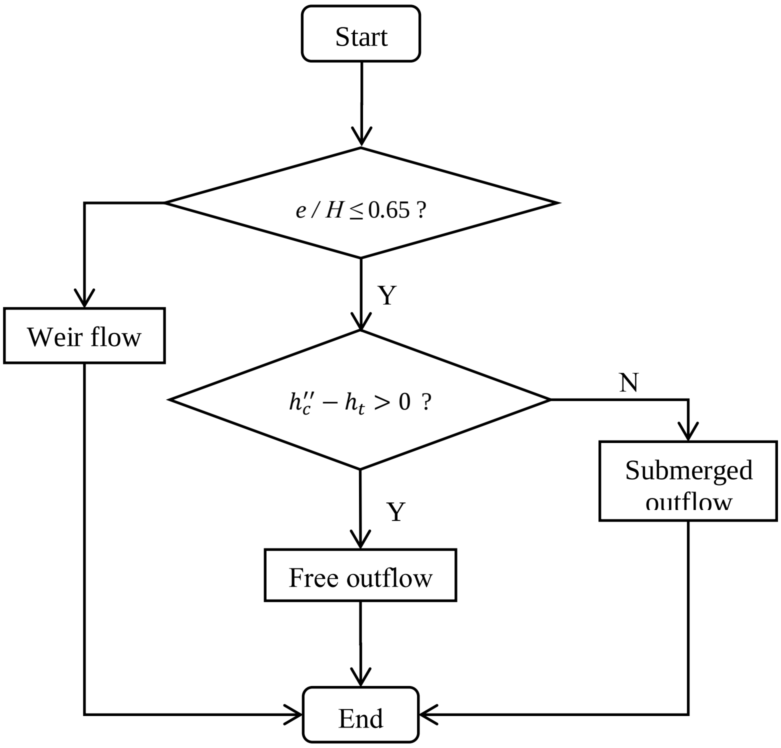


Figure. 2 Flow status judgment flow chart

Conjugate water depth of contraction section after jump is

$$h_c'' = \frac{h_c}{2}\left(\sqrt{1+8F_{rc}^2}-1\right) \quad (1)$$

Wherein

$$F_{rc}^2 = 2\varphi^2(H-h_c)/h_c \quad (2)$$

$$h_c = e\varepsilon \quad (3)$$

$$\varepsilon = 0.6159 - 0.0343\frac{e}{H} + 0.1923\left(\frac{e}{H}\right)^2 \quad (4)$$

Where:

h_c : Water depth of contracted section

F_{rc}^2 : Number of contraction section

ε : Vertical shrinkage coefficient

The flow rate of the gate hole in free flow state is

$$Q = \mu_0 eb\sqrt{2gH_0} \quad (5)$$

Where:

μ_0 : Flow coefficient

b : Gate width

The flow rate of the sluice hole submerged outflow state is

$$Q = \varphi b\varepsilon e\sqrt{2g(H_0 - h)} \quad (6)$$

Wherein

$$h = \sqrt{h_t^2 - M\left(H_0 - \frac{M}{4}\right)} + \frac{M}{2} \quad (7)$$

$$M = 4\mu_0^2 e^2 \frac{h_t - h_c}{h_t h_c} \quad (8)$$

Where:

φ : Velocity coefficient, when the bottom hole under the gate flows out, the value ranges from 0.95 ~ 1.00

ε : Vertical shrinkage coefficient

h : Submerged effective water depth

The flow rate of weir outflow flow state is

$$Q = \sigma m_0 b\sqrt{2g}{h_a}^{3/2} \quad (9)$$

Wherein

$$\sigma = 1.05(1 + 0.2h_t)\sqrt[3]{\frac{H - h_a}{h_a}} \quad (10)$$

$$m_0 = 0.4034 + 0.0534\frac{h_a}{a} + \frac{1}{1610h_a - 4.5} \quad (11)$$

Where:

σ : Flood coefficient of weir flow

m_0 : Velocity coefficient

h_a : Weir head

a : Weir height, a definite value after gate installation

The research results of many experts and scholars show that under different gate types, installation conditions and flow patterns, the calculation parameters of flow measurement of flat gate in open channel are also different, so the flow measurement accuracy will be greatly affected(Wang, Shen, Zhou, Gilles et al.). In this study, the calculation parameters are set as adjustable quantities, so as to facilitate users to adjust according to the use conditions.

2.2 System Structure

The intelligent flat gate system can accurately control the process of canal water supply and distribution by integrating the functions of upstream and downstream water level detection, gate opening and closing control, gate flow measurement and so on. The system mainly includes the in situ measurement and control integration gate device, wireless communication system (Internet control terminal) and the remote monitoring system, in situ measurement and control integration gate device consists of rectangular plate gate, intelligent control system, actuator, sensor and so on, the wireless communication system by using 4G wireless communication network or wireless local area network, WLAN, The remote monitoring system is equipped with remote server, computer, mobile terminal, system operating software, etc.

A complete set of intelligent flat gate system is shown in Fig. 3. Users can send instructions through mobile phone or computer terminal according to their needs, and the intelligent control system drives the corresponding gate to carry out regular and quantitative water distribution; The remote monitoring system is deployed on the remote server of the dispatching center, and remotely monitors the on-site gate device installed on all levels of channels through 4G communication network or WLAN to achieve dynamic water supply and distribution control.

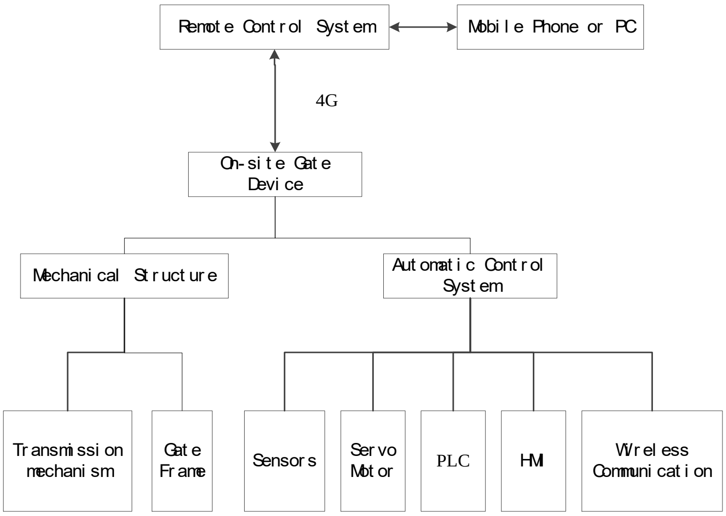


Figure. 3 System composition block diagram

3. Intelligent flat gate design of open channel

3.1 Mechanical structure design

The mechanical structure of intelligent open channel flat gate system is shown in Figure 4, which mainly includes gate frame, gate board, sealing strip, rack and pinion, worm gear and worm reducer, servo motor and sensor, etc.

The screw gate which is often used in irrigated area is easy to get stuck in the process of opening and closing. In this study, the servo motor and worm gear reducer are fixed on the beam of the gate frame, two rack strips pass through the beam, the lower end of which is connected to the top of the gate, the gear is installed on the drive shaft of the reducer, and the gear and rack are engaged well.

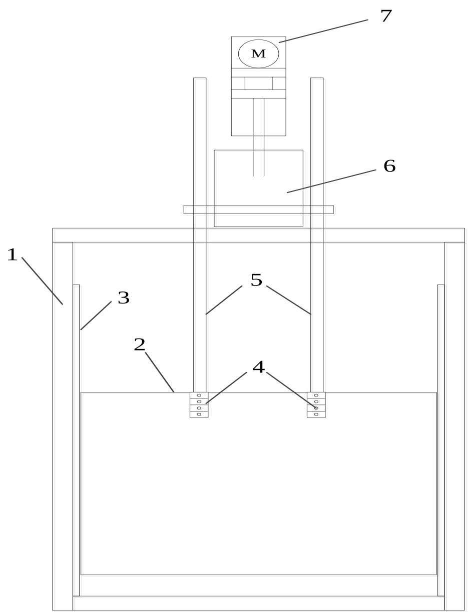


Figure. 4 Mechanical structure of sluice
1. Gate frame 2. Gate plate 3. Sealing strip 4. Connection block 5. Rack 6. Worm gear reducer 7. Servo motor

The net pass width of the gate is 60.0 cm, and the gate opening range is 0.0 ~ 55.0 cm. The incremental rotary encoder is used to collect the gate opening information and feedback the data to the measurement and control system, and its rotating shaft is connected with the reduction gear. Servo motor model is ACM6020V36G-A5, rated power 200 W, rated current 7 A, with brake function, can ensure that the gate in the system power failure to stay in the original position, and compact structure, stable operation.

3.2 Design of automatic control system

The automatic control system of intelligent flat gate has the main functions of gate opening and closing operation control, sensor data collection, gate flow calculation, remote wireless communication, on-site man-machine interaction and information display.

(1) Overall scheme of automatic control system

PLC (programmable logic controller) of SIEMENS S7-200 SMART CPU ST20 is used as the main control module, and the programming design of automatic control is carried out in combination with the calculation process of flow measurement principle of open channel. It includes servo motor drive control, data acquisition, wireless communication, proximity switch, man-machine interface and data storage and other functional modules.

(2) Measurement system design

According to open channel flow measurement theory and method, the intelligent gate is used to calculate the overflow, at least the water level *H* in front of the gate and *H* behind the gate should be measured And gate opening e, etc. The sensor layout in this study is shown in Fig. 5. The water level sensor adopts ultrasonic level meter, and the probes of the two ultrasonic level meters are respectively arranged above the channel where the liquid level is relatively stable upstream and downstream of the gate. Moreover, the installation height of the ultrasonic level meter takes into full consideration the distance of the blind area. The incremental rotary encoder E6B2-CWZ5C is selected as the gate opening sensor, and the gate opening can be measured by recording the rotation speed of the servo motor shaft.

(3) Wireless communication module

Considering that the installation sites of floodgate equipment in irrigation areas are usually scattered and far away from each other, the cost must be high if wired network is deployed, so wireless communication solution is preferred. In this study, the 4G wireless communication module is embedded in the Internet of Things terminal, and the wireless communication function can be achieved through the built-in SIM card in the Internet of Things terminal. The Internet of Things terminal also supports uploading, downloading, and monitoring of PLC programs and touch screen programs, and Web page configuration. If the location of the gate is equipped with a WLAN (such as a Wi-Fi hotspot), the wireless communication function can also be realized through simple Settings of the Internet of Things terminal, which communicates with PLC of the main control module through RS232 interface.

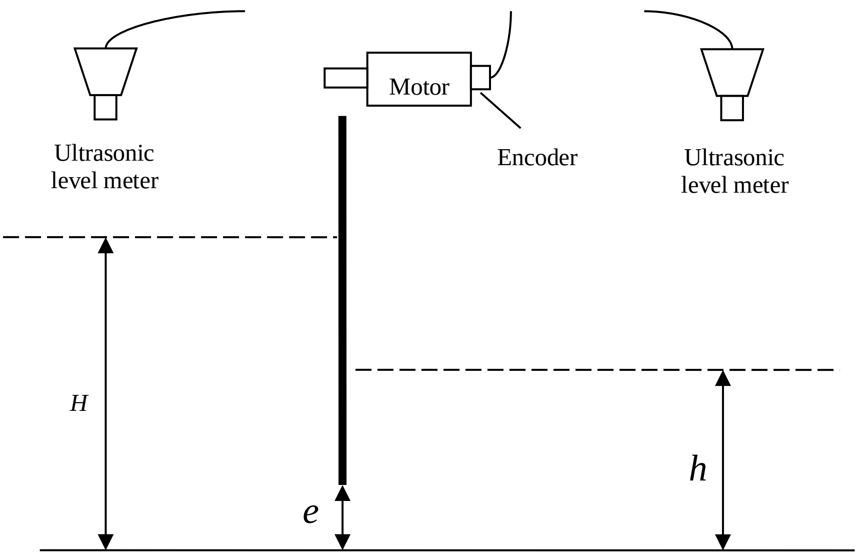


Figure. 5 Sensor installation location

4. Software Design

4.1 Local man-machine interface operation procedures

The configuration editing software Mcgs Pro supporting the man-machine interface is used to design the operation interface, and then the communication connection is established with PLC, so as to realize the local gate automatic control, remote communication, data storage, man-machine interaction, analog monitoring, flow calculation and other intelligent measurement and control functions. The man-machine interface is shown in Fig. 6. In addition, the man-machine interface has encryption function, and the login password is set. Only after the user enters the login password correctly, the user can conduct various interface operations, which improves the operation security of the intelligent open channel flat gate system.

Figure. 6 Human machine interface

4.2 Remote monitoring platform software

The main functions of the remote monitoring platform software include: real-time display of water level and gate opening information, gate lifting control, real-time calculation of gate flow, historical data analysis, abnormal alarm, equipment log, remote download and update PLC ladder diagram program and man-machine interface software program, etc. The control mode of the gate system includes manual and automatic, which can be switched on the interface of the monitoring software. In the automatic mode, the lifting distance of the gate can be set remotely and the gate can run automatically.

Figure. 7 PC interface

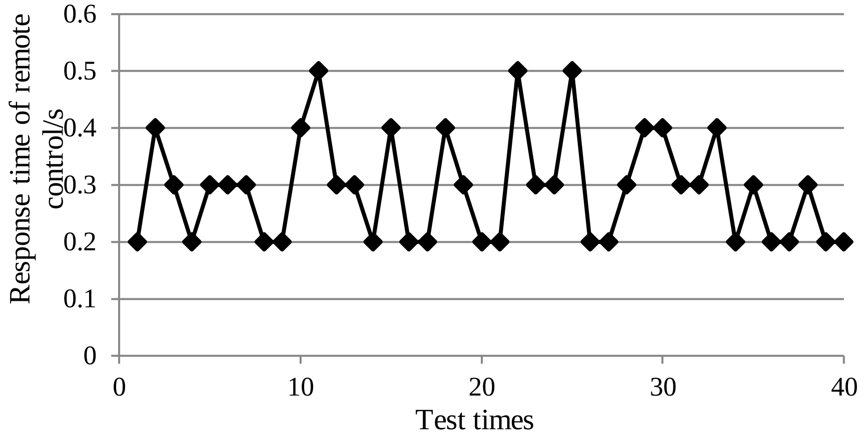
In this study, TN530W4 Internet of Things terminal and its supporting ECSManager software and virtual network port tools are used to connect PLC host and Internet of Things terminal through network cables to design the remote monitoring platform software, including account application, adding items, adding variables, downloading and uploading configuration information, configuration editing, PC and mobile phone viewing, etc. The login website of the remote monitoring platform software on the PC is http://www.ecsiot.net/. Enter the configured user name and password to log in, as shown in Fig. 7. The mobile terminal interface is shown in Fig. 8, which shows various data of the intelligent open channel flat gate system in the laboratory test.

Figure. 8 Mobile phone terminal interface

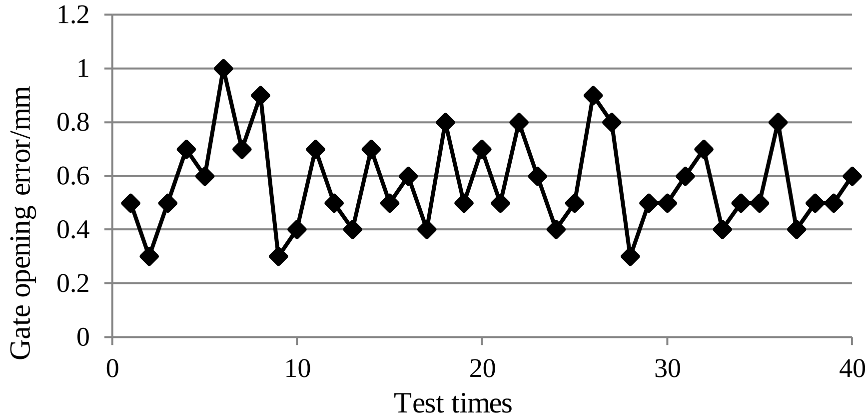
Figure. 9 Test layout

5. Test

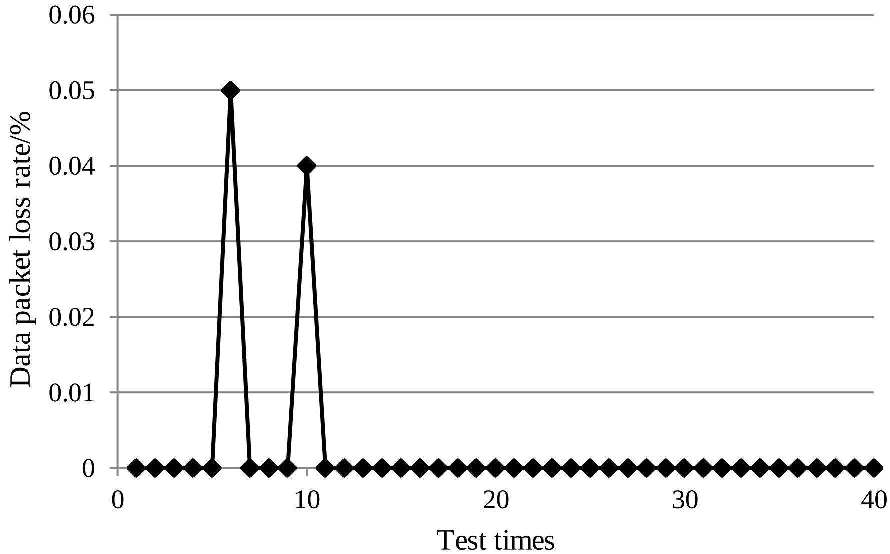
The test was arranged on the intelligent hydraulic test platform of open channel in the Key Laboratory of Water-Saving Irrigation Engineering of the Ministry of Agriculture and Rural Affairs. The channel was made of rectangular tempered glass with a width of 60 cm and a depth of 58 cm. The slope I of the bottom slope was 0.005 24.In order to reduce the impact of turbulence on gate flow measurement, this set of intelligent open channel flat gate system is arranged in the channel 15 m away from the stilling basin, as shown in Fig. 9. The system was tested for 20 days. During the test, the response time of remote control, control accuracy of gate opening and packet loss rate of sensor node data of the system were tested using user terminal devices with different configurations under different signal strength. The test results are shown in Fig. 10. The test results show that the longest response time of remote control of mobile software is 0.5 s, the maximum opening control error is 1 mm, and the network packet loss rate is close to zero. In addition, the gate flow measurement method in literature Zhang et al. is adopted in this system, and the maximum error is 4.6% and 8.3% respectively in free flow and submerged flow states.



(a)



(b)



(c)

Figure. 10 Test results of sluice gate

Figure. 11 Physical picture

6. Conclusion

(1) According to the outlet flow theory of the gate, sensor technology is used to realize the intelligent and integrated measurement and control function of the gate, integrating channel water level monitoring, gate flow calculation and gate opening and closing control and other functions. The intelligent metering and control gate terminal device is developed, which has the advantages of integration and high integration, and is conducive to promoting the informationization and modernization of irrigation districts in China.

(2) Developed the measurement and control gate terminal controller based on PLC, designed the man-machine interface operation software, realized the intelligent control and manual control of the local gate terminal device, suitable for small and medium-sized channel water management.

(3) Based on the Internet of Things technology and 4G wireless communication technology, the gate remote monitoring platform system is developed, which has the remote monitoring, wireless communication and working situation data management functions of the gate terminal, which is conducive to improving the efficiency of channel water transmission and reducing the waste of water resources.

(4) The test results show that the gate terminal device has strong adaptability and stable performance, the gate positioning control precision is 1 mm, the measurement error of free flow is less than 4.6%, and the submerged flow is less than 8.3%. The control precision is high, the response speed is fast, and it has good application value.

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ANALYSIS OF SEDIMENT TRANSPORT IN THE MAIN CANAL OF KANO RIVER IRRIGATION PROJECT

Mustapha Usman Khalil [1]and Salisu Dan'azumi

ABSTRACT

The main canal of Kano River Irrigation Project (KRIP) was designed to ensure that irrigation water is conveyed with minimal erosion and sedimentation, but over time it has been eroded and silted up to the extent that its conveyance capacity has significantly been reduced. This study analyzed sediment transport within the main canal of KRIP using HEC-RAS model. The main canal was divided into three reaches. Yang's equation was used to analyze sediment transport characteristics because of its flexibility, wide sediment class range and ability to compute total sediment load. Parameters required in the model such as canal geometry, discharge, bed and suspended loads were determined through direct measurements and laboratory analysis

. Flow measurements gave 12.11m^3/s, 11.42m^3/s and 10.73m^3/s for Reaches I, II and III respectively. Laboratory analysis for bed load samples indicated higher percentage of gravel of 54.40% and 57.94% in Reach I and II, while higher sand percentage of 74.51% in Reach III. For suspended load sediments, 0.9 mg/l for Reach I and II and 1.1 mg/l for Reach III was recorded. The HEC-RAS model was run with set of data to give cumulative sediment discharge at a time step of 24hrs. The sediment concentration at each cross section within the reach after simulation indicate deposition in Reach III and erosion in Reaches I and II. The invert level of the canal decreases from upstream to downstream after simulation for Reaches I and II while for Reach III, the invert elevation increases at middle of the reach after simulation. This indicates the bed materials are transported from Reaches I and II and deposited along Reach III.

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1. INTRODUCTION

Sediment transport in irrigation canals is an important issue that must be considered in the design and operation of irrigation systems. Irrigation canals are generally designed on the assumption of steady uniform flow of water and sediments. However, the flow is predominantly non-uniform, due to time-dependent discharges and variation of water levels at regulation and division points. Understanding the behaviour and transport of sediment allows efficient planning and reliable water delivery schedules, ensures the controlled deposition of sediments, and make maintenance activities more manageable. Sediment movement is a complex phenomenon, because it is affected by sediment distribution, hydraulic conditions and sediment concentration (Kim et al, 2013). The sediment may move in water either as the bed load or as suspended load. Bed load is that in which the sediment moves along the bed with occasional jumps into the channel while the suspended load is the one in which the material is maintained in suspension due to the turbulence of the flowing water.

Sediment transport in irrigation canals influences to a great extent the sustainability of an irrigation system. Unwanted erosion or deposition will not only increase maintenance costs, but may also lead to unfair, unreliable and inequitable distribution of irrigation water to the end users. Proper knowledge of the characteristics, including behaviour and transport of sediment will help design proper irrigation systems, plan efficient and reliable water delivery schedules, have a controlled deposition of sediments and estimate and arrange maintenance activities. The phenomenon of sediment transport causes large scale scouring and siltation of irrigation canals, thereby increasing their maintenance. Many poorly designed artificial channels get silted up so badly, that they soon become inoperable, causing huge economic loss to the public. (Garg, 2011)

Siltation and design of alluvial channels were addressed by several researchers and development organizations for its impact on national development. According to FAO, the objective of a canal design is to select a bottom slope and geometric dimensions of the cross section such that during a certain period, the sediment flowing into an irrigation canal is equal to the sediment flowing out of the canal. Changes in equilibrium conditions for sediment transport result in periods of deposition or erosion. This study is aimed to analyse the sediment transport in a canal with different lining materials using HEC-RAS model with a view to determining rate of erosion or deposition between them

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2.0 MATERIALS AND METHODS

2.1 Study Area

The study areas is the main canal of Kano River Irrigation Project (KRIP) which starts from Rano Head Works Regulator (RHW) and ends at Gadar Inai. These include clay lined canal section from RHWR to first drop structure a distance of 316m as **Reach I**, stone pitched lined canal section around Garin Babba Town with a distance of 312m as **Reach II** and concrete lined canal section within Kadawa farm center to Gadar Inai with a distance of 578m as **Reach III**. Their descriptions are shown in Table 1.

Table 1: Description of the study area

S/N	Description	Reach Distance (m)	Canal Geometry	Type of Lining
1	Reach I	315	Trapezoidal	Clay Lined
2	Reach II	312	Trapezoidal	Stone Pitched
3	Reach III	578	Trapezoidal	Concrete Lined

2.2 Methods

2.2.1 Flow measurement

The velocity-area method was used for this research. The canal depth and velocity at 5 selected intervals across a canal were measured by the use of wading and cableway, the water depth and the positions across the canal were obtained using a rod for depth and a survey tape for distance. A current meter was used to measure the canal velocity at each selected intervals. The width of the canal was measured using measuring tape, which is then divided in to five strips. The average velocity for each strip was estimated from the velocity measured at 0.2, 0.6 and 0.8 of the depth in that strip. This velocity, times the area of the strip gives the flow for the strip and the total flow is the sum of the strips

Flow (Q_n) for each strip = velocity x area of strip

Total flow in the cross section = $Q_1 + Q_2 + Q_3 + Q_4 + Q_5$ 1

2.2.2 Bed load and suspended load analysis

For bed load sampling, the deposits were first exposed by closing the water in the canal and excavation was made and the depth of the deposit was measured, the samples were taken from the sediment deposit at different points along the canal in order to have good representation of the sediment characteristics of interest. All the samples collected were put in clean polythene bags and then numbered indicating the canal reach where each sample belonged.

The samples collected was air-dried and analysed for particles size according to BS 1377: Part 2: 1990.

The surface and dip sampling method was used for collecting suspended sediment sample, plastic bottles of 1000mls were used for collecting the water samples. The bottles were placed under the water surface by hand until it filled within the mid-stream cross section at a depth of 0.6m of the total depth below the surface. (Osten, 1997). Filtration method was used for the analysis. The amount of suspended sediment (mg/l) was obtained

2.2.3 HEC-RAS model development

The input parameters were both physical and conceptual as shown in Table 2. The value of each parameter was either measured directly, computed from hydrologic equations or already engraved in the model.

Table 2: HEC-RAS input parameters and how they were determined

Physical variables/ Parameters Symbol/unit	Description	Means of determination
d (m)	Particle diameter	Determined from sieving sediment sample
D(m)	Water depth	Measured using tape measure and navigation rod
V(m/s)	Average flow velocity	Measured using the current meter
v(m2/s),	Kinematic viscosity	Provided by HEC-RAS user manual as being computable from measured water temperature
g(m/s2)	Acceleration due to gravity	Constant provided in HEC-RAS user manual (10 m/s2)
γ s(Kg/m2s2)	Sediment specific weight	Constant provided in HEC-RAS user manual (2.65 Kg/m2s2)
γ(Kg/m2s2)	Water specific weight	Provided by HEC-RAS user manual as being computable from measured water temperature
R(m)	Hydraulic radius	Model computation from measured depth and width of flow.
S(m/m)	Slope	Computed from elevation determined by the GPS.
T(oC)	Water temperature	Measured using a thermometer

3.0 RESULTS AND DISCUSSION

3.1 Canal geometry

Canal cross sections were measured at upstream and downstream reach sections and entered in Table 3. From the table it can be seen that the depth of the canal is decreasing from the upstream to downstream which indicates erosion at the upstream and siltation at downstream.

Table 3: Canal cross sections

Description		Reach length (m)	Bed width (m)	Left bank slope (m) 1:	Right bank slope (m) 1:	Depth (m)
Reach I	Upstream	315	10	4	4	2
	Downstream		10	4	4	1.8
Reach II	Upstream	312	11.2	3	3	1.8
	Downstream		11.2	3	3	1.6
Reach III	Upstream	578	7	4	4	1.6
	Downstream		7	4	4	1.3

3.2 Flow Measurement

The flow measurement was conducted at each section using velocity-area method and presented in Table 4. The velocity was obtained by weighted averaging of the velocities at 0.2d, 0.6d and 0.8d using Equation 2

$Vel = 1 / 4 (V_{0.2d} + 2V_{0.6d} + V_{0.8d})$ ………. .. 2

Table 4: Flow measurement data

Reach I				Reach II				Reach III			
Strip	Area (m2)	Vel (m/s)	Flow (m3/s)	Strip	Area (m2)	Vel (m/s)	Flow (m3/s)	Strip	Area (m2)	Vel (m/s)	Flow (m3/s)
1	1	0.10	0.10	1	0.75	0.125	0.094	1	1	0.3	0.30
2	1.8	0.575	1.035	2	1.2	0.75	0.90	2	1.6	0.825	1.32
3	13	0.75	9.75	3	11.2	0.85	9.52	3	8.4	0.925	7.77
4	1.8	0.625	1.125	4	1.2	0.675	0.81	4	1.6	0.65	1.04
5	1	0.10	0.10	5	0.75	0.125	0.094	5	1	0.30	0.30
Total Flow			12.11	Total Flow			11.42	Total Flow			10.73

3.3 Bed load sediment particles size distribution

The deposited sediments are characterized by texture dominated by gravel and sand with small fractions of clay/silt. Gravel fraction dominated the texture in Reach I (54.4%) & II (57.94%) and followed by sand, while the sand fraction is higher at Reach III (74.51%) as shown in Table 5.

The low silt content may be attributed to the excessive washout of the particles by the flowing water, since the particles are light in nature they can move in suspension for a long period. Also, the higher gravel fraction in Reach I and II was due to the fact that the upper reach of the canal was excavated in rock formation starting from Ruwan Kanya reservoir outlet, while the higher sand fraction in Reach III is believed to be washout coming from the farm land upstream. This agrees with the NEDECO (1976) report that the soil of the area was within the range of sandy loam to loamy sand.

Table 5: Particle Size Distribution of the Canal's Sediment

Section	Gravel			Sand			Silt/Clay (%)
	Coarse (%)	Medium (%)	Fine (%)	Coarse (%)	Medium (%)	Fine (%)	
Reach I	0.00	14.80	39.69	27.36	14.40	3.48	0.28
Reach II	0.00	11.61	46.34	28.10	11.41	2.26	0.29
Reach III	0.00	10.28	15.22	45.98	26.61	1.92	0.00

3.3 Invert elevation

Canal bed geometry is another important parameter considered in this research because it shows the level of erosion or deposition across the length of the reach which affects the water surface profile. For Reach I and II it shows that the invert level of the canal is decreasing from upstream to downstream after simulation as shown in Figures 1a and 1b while for Reach III the invert elevation increases at middle of the Reach after simulation as shown Figure 1c. This indicates the bed materials are transported from the Reach I and II and deposited along Reach III.

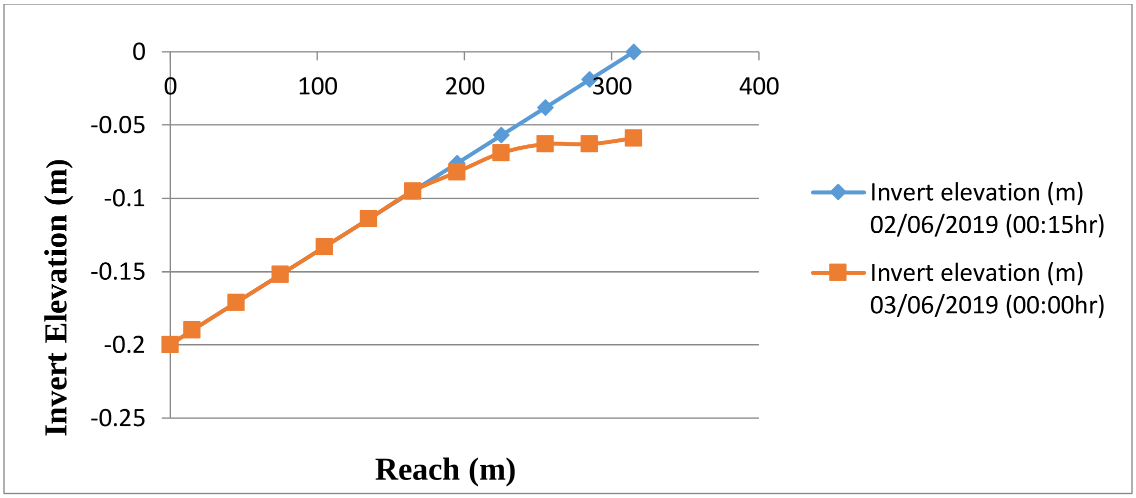

Figure 1a: Invert elevation plot of Reach I at the beginning and end of simulation

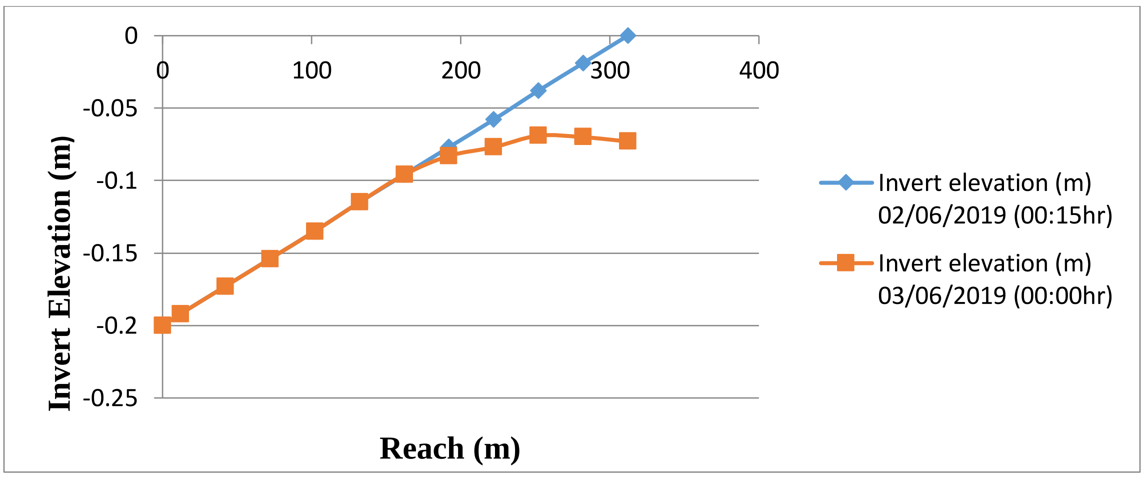

Figure 1b: Invert elevation plot of Reach II at the beginning and end of simulation

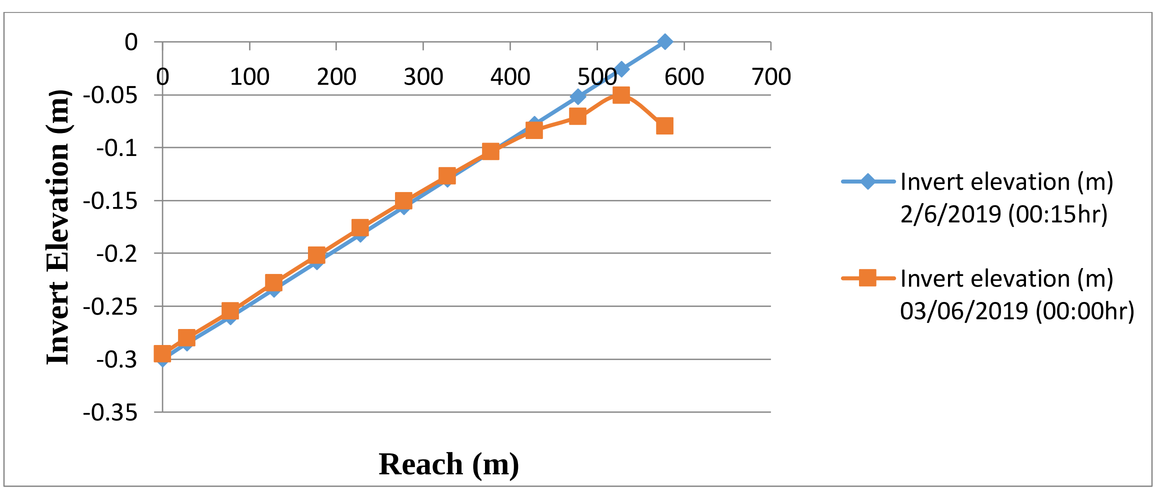

Figure 1c: Invert elevation plot of Reach III at the beginning and end of simulation

3.4 Suspended sediment analysis

Amount of suspended sediment is presented in Table 6. The suspended sediment concentration is higher in reach III (1.1mg/l), this may be due to the fact that the higher the velocity of flow the higher will be the sediment concentration in the canal discharge and the variation in the canal's suspended concentration is connected with the higher amount of sand in the canals and velocity at the time of collection

Table 6: Suspended sediment concentration

S/No.	Section	Concentration of suspended sediment (mg/l)
1	Reach I	0.9
2	Reach II	0.9
3	Reach III	1.1

3.5 Sediment Concentration

The HEC-RAS model was run with sets of input data to give respective outputs of cumulative sediment discharge at a time step of 24hrs. The boundary condition for sediment load series was set based on discharge obtained from flow measurement. The sediment concentration for each cross section within the reach was plotted for both beginning and at the end of the computation.

After running the sediment transport model under the same conditions for a period of 24hrs, the result were encouraging in terms of computing sediment deposition and erosion along the canal. For Reach I and II the concentration of sediment computed by the model before simulation increases at each cross sections from upstream to downstream, while for Reach III the concentration decreases as shown in Figures 2a, 2b and 2c. After simulation for 24hrs the concentration decreases significantly at each cross section for Reach I and II and increases at middle of Reach III.

Figures 2 show the value of sediment concentration at cross sections before and after simulation. The difference between the two gives the amount of sediment deposited or eroded from the canal reach. The total amount of sediment transported in Reaches I, II and III over the simulation period were 2883.56, 3203.79 and 229.93mg/l respectively. These values were obtained by subtracting the total sediment concentration in the reach after simulation from the total sediment concentration before simulation and adding them up together. From these values, there is erosion along Reach I & II and sediment deposition along Reach III.

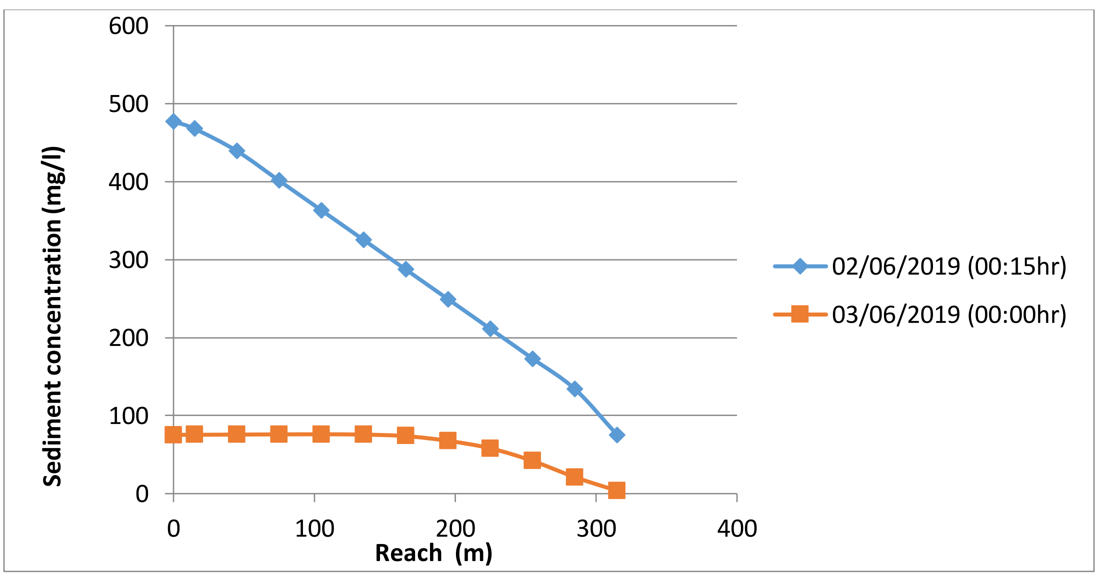

Figure 2a: Sediment concentration plot of Reach I at the beginning and end of simulation

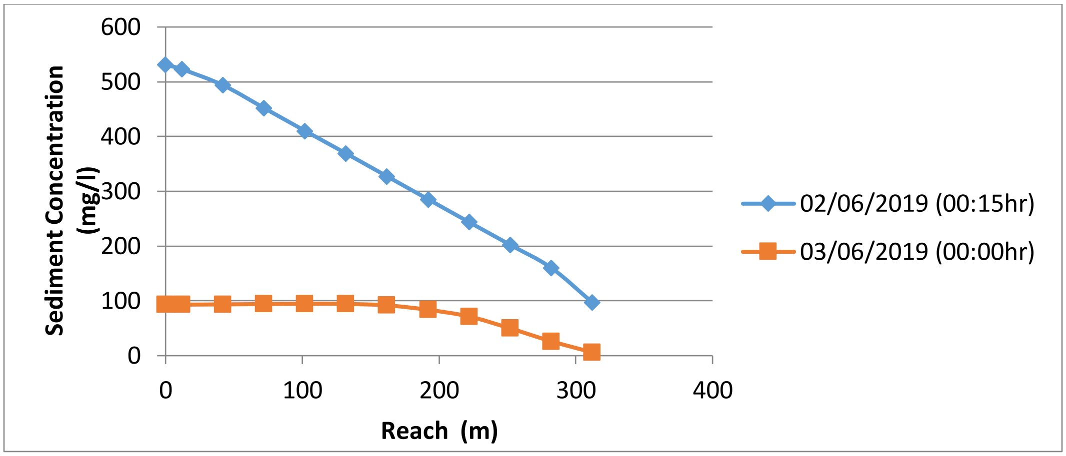

Figure 2b: Sediment concentration plot of Reach II at the beginning and end of simulation

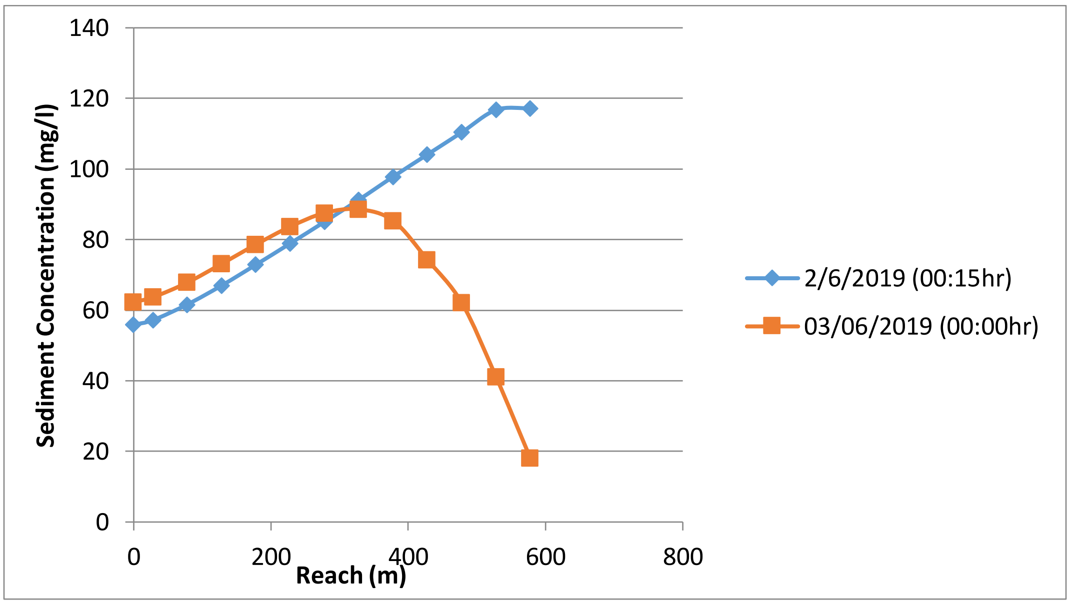

Figure 2c: Sediment concentration plot of Reach III at the beginning and end of simulation

CONCLUSIONS

The analysis of sediment transport in a main canal of Kano River Irrigation Project using HEC RAS model has been carried out, and based on the results obtained, it can be concluded that the sediment transported in Reach I and II are predominantly gravel with 54.4% and 57.94% respectively and the sources is as a result of erosion of bed and canal embankment materials across the Reach by the run-off coming in to the reach from irrigation field. The rate of sediment deposition can be seen clearly in the sediment concentration plot of each Reach after simulation, with the Reach III having the higher deposition rate compared to Reach I and II.

The rate of change in canal bed geometry indicates the extent of erosion and deposition in the canal. From the invert elevation plot at cross sections, Reach I and II show a sharp change in elevation after simulation of up to 145m and 152m respectively from the upstream. While Reach III show a sharp change in elevation after simulation up to 178m from the upstream and then above the initial elevation. It is recommended that concrete lining be adopted throughout the canal's length to permit higher velocities that obviates sedimentation problem in reach I and II. Efforts should be made to reduce the run off coming in to the canal from irrigation field in Reach III by making the canal embankment higher than the irrigation field. The model was run based on a limited data, therefore it is recommended that the model should be improved with sufficient data for efficient simulation.

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ISSUES AND CHALLENGES OF IRRIGATION NETWORKS MODERNIZATION IN IRAN: EXPERT VIEWS

Nader Heydari [1*], Jalal Aboalhasani [2]

ABSTRACT

The water crisis and the necessity of optimal use of water in irrigation networks have highlighted the necessity of modernization of irrigation networks in Iran. Therefore, the main objective of this paper is to asses and evaluates the issues and challenges of modernization of irrigation networks in Iran from the perspective of experts and executives bodies related to the subject. For this purpose, after a fully review of scientific literature on the subject, a comprehensive questionnaire was compiled with the contribution and opinion of the relevant executive bodies in charge of the issue. The main points of the questions raised in the questionnaire were: the necessity and priority of modernization, the level of attention to the issue and the speed of actions, the potential inhibiting factors, the driving and facilitating factors, the impact of modernization on the various components of water management in the network and its agricultural production, effective parameters and necessary criteria in selecting and prioritizing irrigation networks for modernization, internal and external organizational barriers for implementing the modernization process, the extent of the impact of irrigation modernization on actual water saving, and other opinions and suggestions in these regards. Based on the results, the vast majority of the respondents emphasized the necessity of modernization of irrigation networks in Iran. In general, many background-infrastructural factors play a key role in the process of modernization of irrigation networks in Iran. However, components or factors such as policies and laws, institutional and political reforms, volumetric delivery of water, socio-economic criteria, empowerment of utilization systems, definition and main goals from modernization, issues of delivery and distribution of water, O&M costs, effects of modernization on real water saving, and improving the production and livelihood of farmers have a great role in this regard and are highly emphasized by the respondent experts.

Key words: Modernization, Roadmap, Irrigation network, Questionnaire, Water scarcity

INTRODUCTION

FAO defines irrigation modernization as a combination strategy of institutional, managerial and technological changes with the aim of changing from a purely supply-oriented operational mode to a service-oriented one. While the International Commission on Irrigation and Drainage (ICID) defines irrigation modernization as the process of improving the existing project to meet new project criteria. This definition includes changes in existing facilities, operational procedures, management, and institutional aspects (Arif et al., 2019; Burt, 2013). However, some researchers believe that the terms "modern" and "modernization" used in irrigation are relatively vague (Plusquellec, 2009).

Modernization specifically relies on technical, managerial and organizational improvement (as opposed to mere physical reconstruction) of irrigation projects with the aim of improving the use of resources (manpower, water, economy, and environment) and water delivery services to the farms. Such investments for modernization are focused on the details of the internal operation of an irrigation project, rather than simple and large-scale traditional investments in the lining of canals or in the total rehabilitation of projects (Burt, 2013).

Modernization is different from the rehabilitation of the irrigation network. The rehabilitation process refers to renovation operations or improvement and compensation works on irrigation networks and related facilities that need repair or facilities whose performance does not meet the standards and needs foreseen in the initial plan. The rehabilitation process also includes modification or revision in the policies and methods of network operation, management and related administrative and legal aspects. The purpose of the rehabilitation is to improve the economic and social benefits of network water consumers (Siahi, 2010). In different literature, the terms rehabilitation and modernization are usually used together, and although the scope and type of their activities differ to a large extent in terms of the nature of making modifications, improvements or changes in the existing systems, but it can be said that there are some common tasks in each of these two types of activities (Siahi, 2010).

Modernization is a process that determines specific goals and selects specific actions and tools to achieve them. Irrigation projects planners and engineers often equate modernization with actions such as lining of the canals

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and computerizing the system. If the process required to improve system performance is evaluated, such investments are often have the lowest priority. According to the FAO (2007), irrigation modernization is often misunderstood and associated exclusively with the use of high technology or costly automation of the system. However, modern irrigation management is basically related to responding to the needs of current users with optimal use of existing resources and technologies, as well as predicting the future needs of the project.

It is estimated that large-scale gravity irrigation networks comprise about 60% of irrigated lands around the world. Therefore, large-scale irrigation networks are a major part of irrigated agriculture, which supplies 40% of the world's food and fiber production. There are lots of evidences that the performance of large-scale irrigation networks is much lower than anticipated (Plusquellec, 2009).

Considering the expansion of urbanization and rapid industrialization, the competition for water use between the irrigated agricultural sector and other water consumers will be a serious challenge and issues in the world. Because all these sectors have to use and share limited water resources. Therefore, one of the main tasks of the water (irrigation) management in the agricultural sector will be to reduce water losses and to achieve equitable water delivery and distribution among the water users. Therefore, modernization of irrigation networks will be an essential part of tackling the challenge and solving of the problem.

The specific goals of modernization include: increasing water productivity, increasing investments effectiveness, increasing the reliability and flexibility of irrigation water supply according to the demand of other users and meeting environmental needs (Playan and Mateos, 2006).

Modernization processes are complex and their characteristics are location-oriented and dependent on the socio-economic and environmental conditions of each region and country. An in-depth analysis of the irrigation modernization process for each case study should be centered around the following four main questions (Tarjuelo et al., 2015): 1- What factors caused the movement towards the modernization of the irrigation system, 2- What types of actions were taken in that process, 3- What were the effects of these actions, and 4- What lessons were obtained or learned?

Most irrigation modernization policies are focused on providing infrastructure and new technologies to improve the efficiency of irrigation water conveyance and use. These policies have prevailed in most arid and semi-arid countries. In many cases, there has been no regional-scale reflection on their impacts, and no comprehensive review of its future policy direction (Sanchis-Ibor et al., 2021).

FAO has developed methodologies for analyzing large irrigation networks. MASSCOTE, which is actually an abbreviated word for "Mapping System and Services for Canal Operation Techniques”, is one of them. MASSCOTE is a step-by-step methodology to evaluate and analyze different components of an irrigation system, and then the irrigation modernization program is implemented. The modernization program includes the improvement and promotion of various physical, structural and administrative components to improve water delivery services and the effective cost of managing and operating irrigation networks. The first part of MASSCOTE is the evaluation and analysis of current conditions, processes and operations. In the second part, a vision for the irrigation system is planned and implemented, and modernization improvement processes are planned to achieve these goals (Amiri Takaldani and Samadi, 2014).

Population growth and higher demand for water for the production of agricultural products, occurrence of droughts and climate change have led to a sharp decrease in water resources and shortage of water needed in the agricultural sector, as the largest water consuming sector in Iran. Out of about 8 million hectares of irrigated lands in the Iran country, about 3.2 million hectares of lands are under irrigation networks, out of which 2.2 million hectares are equipped with main irrigation networks and in 1.0 million hectares the network is fully complete and is equipped with secondary and tertiary canal systems levels together with on-farm improvement activities (in 1.4 million hectares).

Because of the shortage in water resources stored behind dams and other water supply systems, currently out of 3.2 million hectares of the irrigation networks in Iran, only 2.9 million hectares are working in practice. The water crisis and the necessity of optimal use of water in the irrigation networks have made the necessity of modernization of the country's irrigation networks more visible and important.

Review of the scientific literature as well as the laws, policies, and national documents, e.g. the five-year development plans, on country’s water management, shows that the modernization of irrigation networks has not been addressed and or paid enough attention. Consequently this subject has not been directly and or explicitly included in the plans and budgeting of relevant executive bodies and organizations.

This research was carried out in line with the first stage of a comprehensive investigation regarding the subject of irrigation networks modernization and the general goal of compiling a road map for the modernization of irrigation networks in the conditions of a severe shortage of water resources in the Iran country. Therefore the main objective of this paper is to study the issues and the general challenges of modernization of irrigation networks from the point of view of relevant experts and stakeholders and as a preliminary evaluation of the subject in the Iran country.

METHODOLOGY

Following a comprehensive review of scientific literature on the subject of irrigation modernization in Iran and the world, as well as discussions and specialized meetings with the relevant experts, especially managers of executive bodies, views, components, factors, and the key pivots issues of the subject were determined. Then a comprehensive questionnaire for the purpose of seeking expert opinions on the different questions regarding modernization of irrigation networks in Iran was developed. It consisted of 67 specific questions that covered various aspects related to the issues and challenges of irrigation modernization in the country and with a global view.

The filled questionnaires were collected from a number of 60 people including experts and managers of water and agriculture related government agencies, water resources management companies, consulting engineers, university professors, researchers and other experts related to the subject.

The main points of the questions raised in the questionnaire were: the necessity and priority of modernization, the amount of attention to the issue and the speed of actions, the potential inhibiting factors, the effective driving and facilitating factors, the impact of modernization on the various components of water management in the network and its agricultural products, effective parameters and necessary criteria in selecting and prioritizing networks for modernization, internal and external obstacles for implementing the modernization process, the extent of the impact of modernization on real water saving, and other relevant comments and issues.

For the statistical analysis, Likert scale (spectrum) method (five parts) was used. Therefore, by receiving the answers to the questions from the respondents, according to the Likert scale, the resulting data were analyzed statistically.

Considering that the questions of the questionnaire included five-choice questions, i.e., very much, much, moderate, little, and very little; or strongly agree, agree, neutral, disagree, and strongly disagree, the level of desirability was defined in five levels including: completely favorable, relatively favorable, somewhat unfavorable, unfavorable, and completely unfavorable, respectively. The weight or numerical score of these levels was considered equal to 5, 4, 3, 2, and 1, respectively.

According to the frequency of answers related to each of the options in each question, the weight score of each question (or indicator) was calculated and it was matched with the mentioned five-part Likert spectrum for determining of desirability level of the question (Mohammadi and Bazargan Herandi, 2004).

Then, a qualitative analysis of the results of the evaluation of the opinions of the respondents, based on the desirability levels, for various questions was carried out and presented in the form of different categories.

RESULTS AND DISCUSSIONS

Based on the results of the above mentioned statistical analysis, the qualitative analysis of the results of the evaluation of the opinions of the respondents to different questions and based on the desirability level was conducted. These qualitative results indicates the preliminary strategies and issues that should be addressed in the modernization of irrigation networks in Iran, which are presented in different categories of the question's desirability levels in below.

A- Desirability levels: Completely favorable (N=8 out of 67 cases)

- Water and agriculture policies and laws play a very high role as driving factors for irrigation modernization.
- The need to carry out the necessary institutional and political reforms in the proper management of water use in the agricultural sector, including the greater participation of stakeholders, are very important and effective as driving and facilitating factors for the modernization of irrigation networks.
- Modernization of irrigation network has a great impact on improving the volumetric delivery of water in the network.
- The role and importance of socio-economic criteria in selecting and prioritizing irrigation networks for modernization is very high.
- The role and importance of criteria such as land and water resources utilization systems in selecting and prioritizing irrigation networks for modernization is very high.
- Choosing the networks that better respond to modernization is a very important criterion.
- With the definition that "Irrigation modernization is about improving water delivery and distribution services to users, reducing operating costs for farmers, facilitating operations, improving agricultural production in a sustainable manner and improving livelihoods of rural communities should also be focused", there is strong agreement.

- There is strong agreement that the failure to establish, and empower water and land utilization systems is a potential obstacle in implementing the process of modernization of irrigation networks.

B- Relatively favorable (N=48 out of 67 cases)

- Modernization of irrigation networks is very necessary.
- The priority of modernization of irrigation networks is high compared to other necessary measures and activities of infrastructure affairs in soil and water issues.
- There is a great need for modernization of irrigation networks.
- The lack of proper definition and clear goals from modernization in the Iran country is a very important obstacle in the modernization process.
- The lack of funds and necessary budget has a great contribution in preventing the modernization of irrigation networks.
- The lack of feeling of necessity, lack of will, or the lack of necessary belief between managers and related executive bodies is a great deterrent factor in preventing the modernization of irrigation networks.
- The lack of a plan and or road map for the modernization of irrigation networks, potentially has caused a large amount of hindrance in the modernization of irrigation networks.
- Scarcity in water resources in irrigation networks due to drought and climate change, play a great driving role in facilitating and advancing the modernization of network.
- The role and importance of agriculture in achieving food security from the country's limited water resources are also important driving factor for the modernization of irrigation networks.
- The need to change the system's attitude towards network management and the greater participation of stakeholders in network management has a great driving and facilitating role in the modernization of irrigation networks.
- The low performance and performance deficit in irrigation networks and the need to increase their performance have a great driving and facilitating role in the modernization of the networks.
- The increase in population and the need to produce more food with less water has a great driving and facilitating role in the modernization of irrigation network.
- Weakness in the traditional methods of rehabilitation of irrigation networks and the need for a new approach for modernization, have a great role and influence as factors that drive and facilitate the modernization of irrigation networks.
- Availability of new knowledge and the need for mainstreaming, training, and capacity building in managers, experts, and users regarding new methods of water management in networks, including in the field of modernization of irrigation networks, all have a great role as driving factors and facilitators of network modernization.
- The lack of necessary evaluations and knowledge from the modernity level of irrigation networks in the current state and the need for modernization in them have a great importance and role as driving factors and facilitators of irrigation network modernization.
- High losses of water and the need to improve volumetric water allocation to the farmers to increase network performance and to improve water productivity are among the most important driving factors in the modernization of irrigation networks.
- Modernization of irrigation networks has a great impact on improving equity and adequacy of water delivery and distribution in networks.
- Modernization of irrigation networks greatly improves the performance of agricultural products in the network.
- Modernization of irrigation networks improves the economy of the network to a great extent.
- Modernization of irrigation networks greatly leads to optimal use of basic resources (water, soil, etc.) in the irrigation network.
- Physical-structural criteria have a great role and importance in selecting and prioritizing irrigation networks for modernization.
- Technical and technological criteria have a great role and importance in selecting and prioritizing irrigation networks for modernization.

- Network stability criteria have a great role and importance in selecting and prioritizing irrigation networks for modernization.
- The production policy in the irrigation network is a criterion of great importance in the selection of networks for modernization.
- Proportion in the capacity of irrigation canals compared to the size of the irrigated area is one of the most important criteria in the modernization of irrigation networks.
- Consideration of the water requirement of the lands and the variety and volume of water resources used in the network are very important criteria in the modernization of irrigation networks.
- Consideration of the spatial and temporal variation of demand caused by variation in soil texture, precipitation pattern, variety of cultivated crops, soil quality, land ownership, the state of land boundaries, and land consolidation, are among the most important criteria in modernization of irrigation networks.
- Consideration of the structural-technical issues in the irrigation network (including: capacity of canal, canal slope, slope of land, type of control structures and volume delivery of water, presence of compensatory water tanks in farm systems, and method of water distribution (gravity or pumping) is one of the most important things in the modernization of irrigation networks.
- It is very important to consider the issues of water rights systems in the process of modernization of irrigation networks.
- Paying attention to the capabilities and operational capabilities of the irrigation agency and water users associations (WUAs) in the irrigation network is of great importance in the modernization of irrigation networks.
- There is agreement with the definition that "irrigation modernization is a combination of institutional, managerial, and technological changes with the aim of changing the approaches from a purely supply-oriented operational mode to a service-oriented one."
- There is agreement with the definition that "irrigation modernization is the process of improving the existing project to meet new project criteria (change in existing facilities, operational procedures, management and institutional aspects)".
- There is agreement on this discussion that "modernization is a dynamic phenomenon and process".
- There is an agreement that the weakness in intuition, knowledge, or insufficient related trainings at the level of irrigation network experts is a potential obstacle in the implementation of the modernization of irrigation networks.
- There is agreement that the weakness in intuition, knowledge, or insufficient related trainings at the level of irrigation network managers is a potential obstacle in implementing the process of modernization of irrigation networks.
- There is an agreement that the existence of old rules, criteria, and procedures for design and implementation and weakness in the elements of the plans for innovative plans, acts as a potential obstacle in the implementation of the process of modernization of irrigation networks.
- There is agreement that the lack of specialized and skilled manpower is a potential obstacle in implementing the process of modernization of irrigation networks.
- There is an agreement that the experiences gained from the hasty design and the hasty and quick start of the modernization work (in the cases of international and national experiences) can be a potential obstacle and deterrent in the implementation of the irrigation network modernization.
- There is agreement that deficiencies in the use of interdisciplinary knowledge, especially in dealing with social aspects, are a potential and infrastructural obstacle in the implementation of the process of modernization of irrigation networks.
- There is agreement that the lack of applied research and published articles on the subject in the academic and research circles of the country is a potential and infrastructural obstacle in the implementation of the process of modernization of irrigation networks.
- There is agreement that the problems and shortfalls in the volumetric delivery of water to the users are a potential and infrastructural obstacle in the implementation of the process of modernization of irrigation networks.
- There is an agreement that the need to rehabilitate the networks before the implementation of the modernization program and the problems and high costs associated with it, is an important potential obstacle in the implementation of the modernization process of irrigation networks.

- There is agreement that the experiences of non-compliance of network reconstruction or rehabilitation with modernization goals can be a potential obstacle and deterrent in the implementation of the modernization process of irrigation networks.
- There is an agreement that the issues of water rights and the need to modify or organize them are potential and infrastructural obstacles in the implementation of the process of modernization of irrigation networks.
- There is agreement that infrastructural issues and problems, financial arrangements, payment of subsidies and financial support, and other related economic issues are a potential and infrastructural obstacle in the implementation process of modernization of irrigation networks.
- There is agreement that lack of a localized model and road map to start the modernization process in irrigation networks is a potential and infrastructural obstacle in its implementation.
- There is agreement that the lack of appropriate mechanisms to use the capacities of the private sector in the implementation and operation of irrigation networks (including the modernization of networks) is a potential and infrastructural obstacle in the implementation of the irrigation modernization process.
- The respondents generally agree that the effectiveness of modernization of irrigation networks as a solution to real water saving is high.

C- Somewhat unfavorable (N=8 out of 67 cases)

- The contribution of the non-availability of special tools for the modernization of irrigation networks as an obstacle for this task is moderate.
- The increase in energy consumption and related costs in irrigation networks for the users has a moderate inhibiting role in modernization.
- The lack of existing knowledge and experience on the subject at the national level has a moderate inhibiting role in modernization.
- There is an abstention (neutral) opinion that the lack of teaching materials or related trainings in university courses for irrigation engineering and other related fields act as an obstacle to modernization.
- There is an abstention opinion in this discussion that "basically, the terms "modern" and "modernization" used in irrigation networks are relatively vague".
- There is an abstention opinion in this discussion that the lack of weakness of specialized and skilled consulting engineering companies in the field of modernization of irrigation networks in the country acts as an important and potential obstacle in the implementation of modernization of irrigation networks.
- Regarding the weakness or lack of relevant technical standards and criteria as an obstacle to modernization, there is an abstention opinion.
- Regarding the issues of sanctions and relative lack or inappropriate supply of good quality modern equipment for construction or spare parts for O&M of irrigation networks, as an important and potential obstacle in the implementation of the network modernization process, there is an abstention opinion.

D- Unfavorable (N=3 out of 67 cases)

- The extent of attention paid to the modernization of irrigation networks has been low.
- The work speed of the necessary measures for the modernization of irrigation networks has been slow.
- Sanctions and the lack of necessary technologies and tools have been a small hindrance factor on the way to modernization.

E- Completely unfavorable (N=0 out of 67 cases)

- There was no case.Results of the qualitative analysis of the opinions of the respondents indicate that the questions with the desirability level of “completely favorable” are the most frequent (48 out of 67; 72%) one. Followed by the questions with the desirability level of “relatively favorable” (8 cases; 12%), “somewhat unfavorable” (8 cases, 12%), “unfavorable” (3 cases; 4%), and “completely unfavorable” (no case; 0%) are placed. On this basis, the key components and factors related to the subject of modernization of irrigation networks in Iran could be presented in summary as shown in Figure 1.

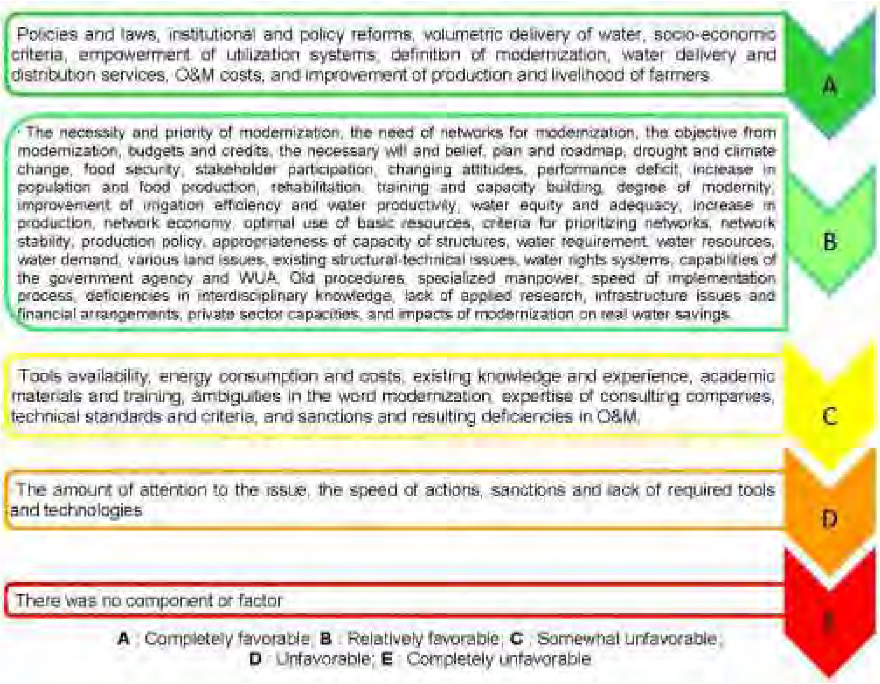

Figure 1. Components and key factors relevant to the modernization process of irrigation networks in Iran along with their importance rating from the point of view of the respondents.

CONCLUSIONS AND RECOMMENDATIONS

Considering the crisis of scarcity in water resources in the Iran country, the proper use of limited water resources for the production of agricultural products and ensuring the food security of the country, especially through the irrigated lands under the irrigation networks, is essential. Attention activities on improving performance of irrigation networks will lead to optimum utilization of huge investments paid for their construction and operation thorough best use of surface water sources which in turn will help to reduce high withdrawal and extensively overexploitation of ground water resources in the country. Modernization of irrigation networks along with other infrastructure activities on water and soil issues in the irrigation networks will play an effective role in this regard. The results of soliciting opinions from experts on the subject and quantitative and qualitative analysis of the respondents' opinions, as the first step in planning and developing a road map for the modernization of irrigation networks, indicate that there is a lot of general agreement on this matter.

The results of counting and evaluating various key and effective components and factors regarding the process of modernization of irrigation networks with different degrees of importance (more than 50 components with very high to high degree of importance) indicate that the implementation of this process is complex and it requires many factors, variables, and infrastructure to be available. It is on this basis that most scientific literature recommend that this process should be gradual and with sufficient study.

Overall, many background-infrastructural factors play a role in the process of modernization of irrigation networks in Iran. However, components or factors such as policies and laws, institutional and political reforms, volumetric delivery of water, socio-economic criteria, empowerment of utilization systems, definition and main goal from modernization, issues of delivery and distribution of water, O&M costs, effects of modernization on real water saving, and improving the production and livelihood of farmers, have a great role in this regard.

The impact of modernization on various performance indicators of the network, especially the actual water saving, the purpose and specific definition of modernization, the way of participation of stakeholders in the work process, and the issues of O&M after modernization process, are among the important issues that need further studies.

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AN AUTOMATIC PRECISION IRRIGATION AND DRAINAGE SYSTEM FOR FARMLAND WITH LOW ENVIRONMENTAL IMPACT

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ABSTRACT

In order to solve the problem that the existing farmland irrigation and drainage mode can not effectively reduce the non-point source pollution of farmland, this paper developed a low environmental impact farmland automatic precision irrigation and drainage system. The system includes a data acquisition subsystem, a field water quantity control subsystem, a water quality monitoring subsystem and a channel drainage measurement and control subsystem which are connected by communication in turn.

The data acquisition subsystem is used to collect the video data of crop growth situation, field meteorological data and field water level data. The field water volume control subsystem is used to dynamically adjust the inflow and outflow of farmland according to the field meteorological data and the field water level data. The water quality monitoring subsystem is used to automatically monitor the water quality indicators of farmland drainage. The channel drainage measurement and control subsystem is used to dynamically control the drainage volume from the field channel to the river according to the water quality index of the field drainage.

Keywords: Farmland; Irrigation district; Drainage reduction; Low environmental impact

1. Introduction

The traditional farmland irrigation and drainage technology mostly uses channels and pipes for irrigation. The management personnel control the water inflow and drainage through the computer and mobile terminal control gate and electric valve on the site. The management scope is too wide, and the operation is time-consuming and laborious. At the same time, the management personnel grow crops through experience. The farmland irrigation still uses the flood irrigation mode. In addition, excessive use of chemical fertilizers and unreasonable irrigation methods lead to low absorption and utilization rates of fertilizers and medicines for crops.

Taking nitrogen and phosphorus as an example, nitrogen absorption rates account for 30-50% of the fertilizer amount, phosphorus absorption rates account for 15-25% of the fertilizer amount, and 70% of fertilizers and medicines are directly discharged into the river through drainage, resulting in non-point source pollution in the river. Controlling the loss of farmland chemical fertilizers is crucial to prevent and control non-point source pollution in China, The automatic irrigation and drainage integration system with low environmental impact aiming at reducing agricultural non-point source pollution emissions has not yet appeared.

2. System design

As shown in Figure 1, the automatic precision irrigation and drainage system for farmland with low environmental impact is composed of data acquisition subsystem, field water volume control subsystem, water quality monitoring subsystem and channel drainage measurement and control subsystem. The data acquisition subsystem is used to collect the video data of crop growth trend, field meteorological data and field water level data. The field water volume control subsystem is used to dynamically adjust the water inflow and outflow of farmland according to the field meteorological data and field water level data.

The water quality monitoring subsystem is used to automatically monitor the water quality indicators of farmland drainage. The channel drainage measurement and control subsystem is used to dynamically control the drainage volume from the field channel to the river according to the water quality index of farmland drainage.

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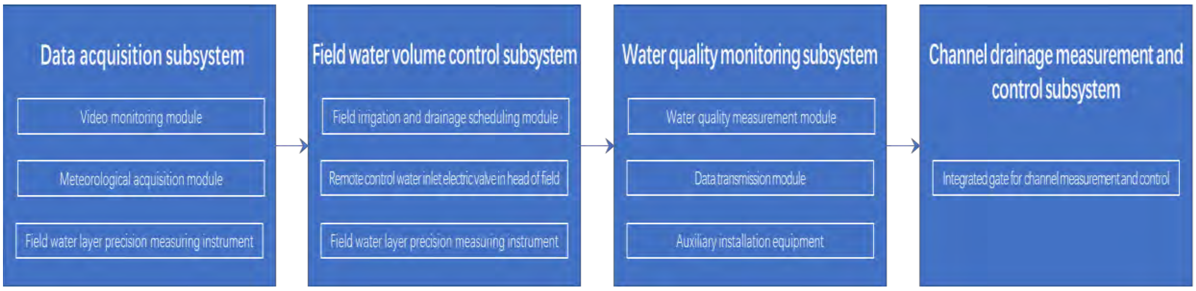

Figure 1 Structural block diagram of a low environmental impact farmland automatic precision irrigation and drainage system

2.1 Data acquisition subsystem

The data acquisition subsystem includes video monitoring module, meteorological acquisition module and field water layer precision measuring instrument. Among them, the video monitoring module is used to collect the video data of crop growth situation in farmland and generate the corresponding crop irrigation scheme; The meteorological acquisition module is used to collect the field meteorological data of farmland, and automatically alarm when meteorological disasters are detected; The field water level precision measuring instrument is installed at the relative horizontal points in the farmland, and the field water level data of the farmland are collected by using the ultrasonic non-contact high-precision measurement mode.

The video monitoring module includes a front-end camera and an expert diagnosis platform. The front-end camera is installed at the position with a wide field of view beside the ridge, which is used to collect the video data of crop growth situation in the farmland; The expert diagnosis platform is used to generate the corresponding crop irrigation scheme according to the video data of crop growth trend. The video monitoring module equipment supports a variety of sensor interfaces and audio and video functions. It is a wireless video monitoring system for agricultural production process monitoring and disaster prevention and control special applications. It can effectively provide users with first-hand crop growth trend data and guide the generation of irrigation schemes that are more suitable for the actual growth environment and growth law of crops.

The meteorological acquisition module includes sensor equipment and alarm. The sensor equipment supports MODBUS communication, opens the communication protocol, provides the communication protocol procedure and opens OPC code. The main module complies with the DZZ4 observation station or higher model standard of the National Meteorological Administration, and is installed in the open position of farmland. It includes air temperature sensor, air humidity sensor, wind speed sensor, wind direction sensor, rainfall sensor and air pressure sensor, which are used to collect the temperature, humidity, wind direction, wind speed Rainfall and pressure are the six meteorological observation elements. The alarm is used to automatically send out alarm signals when strong wind, rainstorm, high temperature, heat damage, ice and snow, frost, cold dew wind and other meteorological disasters are detected. The meteorological collection module provides the analysis basis for the spatial refinement of conventional meteorological elements by building a modern, standardized and standardized observation network of conventional meteorological elements in natural farmland, which can timely intervene in the field water volume control subsystem, reduce the impact of natural disasters on crops and ensure the growth of crops.

The precision measuring instrument of field water layer is distributed at the relative horizontal points in the farmland. The ultrasonic non-contact high-precision (mm level) measurement mode is used to collect the field water level data of the farmland, and the wireless communication intelligent execution system is equipped. The agricultural growers use the portable mobile central server to send instructions, and the field wireless communication execution terminal controls the field water layer precision meter to perform accurate measurement, and feeds back the measurement data to the upper computer, which controls the operation of the field water volume control subsystem according to the received data.

2.2 Field water volume control subsystem

The field water volume control subsystem includes the field irrigation and drainage scheduling module, the field head remote control water inlet electric valve and the field automatic drainage gate. The field irrigation and drainage scheduling module is used to send the opening command to the remote remote water inlet electric valve or the field automatic drainage gate at the head of the field according to the rain storage thin dew irrigation model. The specific model of rain storage and thin dew irrigation is: when the field water level data reaches the lower limit, send the opening command to the remote remote control electric inlet valve at the head of the field; When there is no rainfall in the field, if the water level data in the field reaches the upper limit of irrigation, the opening command will be sent to the automatic drainage gate in the field; When it rains in the field, if the field water level data reaches the upper limit of rainfall storage, the opening command will be sent to the field automatic drain gate.

The remote remote control electric water inlet valve at the head of the field is installed at the water inlet of the farmland, with a LORA wireless control module built in and in a normally closed state. It supports remote control and local emergency control. The software is designed using Java to realize the automation, intelligence and informatization of farmland water-saving irrigation and optimize the allocation of water resources. After receiving the opening command sent by the field irrigation and drainage dispatching module, the remote remote control electric water inlet valve at the head of the field is opened to precisely control the irrigation water layer in the field, so as to realize unmanned patrol in the field and self irrigation management control.

The field automatic drain gate is installed at the field outfall and is normally closed. After receiving the opening command sent by the field irrigation and drainage dispatching module, the field automatic drain gate is opened to ensure the normal water level of the farmland. The automatic drainage gate in the field can complete the irrigation and drainage work by itself to achieve the purpose of automatic drainage and unattended.

2.3 Water quality monitoring subsystem

The water quality monitoring subsystem includes water quality measurement module, data transmission module and auxiliary installation equipment. The water quality measurement module is used to automatically monitor the five water quality indicators of farmland drainage, namely, chemical oxygen demand, permanganate index, ammonia nitrogen, total phosphorus and dissolved oxygen. It is used to evaluate the water quality of farmland drainage, guide the use of fertilizer in farmland, and provide control basis for the channel drainage measurement and control subsystem to conduct farmland drainage into the river. The data transmission module is used for wireless remote transmission of water quality indicators to the upper computer client through GPRS, RTU or CDMA, without the need to build a specific water quality automatic monitoring station. The auxiliary installation equipment is the outdoor standing pole without station, which is used to install the water quality measurement module and data transmission module at the field channel estuary.

2.4 Channel drainage measurement and control subsystem

The channel drainage measurement and control subsystem includes the channel measurement and control integrated gate, which is installed at the estuary of the field channel. When the rainfall is greater than the preset rainfall threshold and the water quality indicators of farmland drainage meet the discharge requirements, the channel measurement and control integrated gate is opened to discharge the channel water into the river. When the water quality indicators of farmland drainage do not meet the discharge requirements, the channel measurement and control integrated gate is closed to reduce the river non-point source pollution, When the water level of the river is higher than the preset water level threshold, the integrated gate of channel measurement and control is closed to prevent the river from flowing back into the field. The channel drainage measurement and control subsystem integrates the functions of wireless communication remote control water level measurement, flow measurement, accurate flow control, and solves the problem of farmland drainage terminal control.

The data acquisition subsystem, field water volume control subsystem, water quality monitoring subsystem and channel drainage measurement and control subsystem are powered by solar cells, which are clean, environmentally friendly, energy efficient.

3. Application effect analysis

Rice water-saving irrigation technology achieves the goal of water saving and emission reduction by making full use of rainfall, reducing irrigation and drainage times and irrigation and drainage volume. However, in practical application, it is found that the management level of water drafters, the water storage capacity of rice fields, and especially the difficulty in managing the existing farmland irrigation and drainage control devices have become the difficulties in the promotion of this technology. The development of double ram overflow type paddy field precision irrigation and drainage control device provides a simple and easy means for the popularization and application of rice water-saving irrigation technology. After the development and patent application of the double ram overflow type paddy field precision irrigation and drainage control device, the device will be used and observed in Pinghu Irrigation Test Station in Zhejiang Province in 2021, and has been promoted in 16 small irrigation areas in Pinghu City, with more than 3000 mu. The rice planting in Pinghu City, Zhejiang Province is dominated by single cropping rice. The growing season in 2021 is from June to November. The method of rice rain storage and thin dew irrigation is adopted. Thin dew irrigation is a kind of irrigation technology for rice to irrigate thin water layer and timely dry open field. In order to improve the utilization rate of rainwater, Pinghu City has formulated the field water layer control standard for rain storage thin exposed irrigation. See Table 1 for details.

Table 1 Field Water Layer Control Standards for Rainfall Storage and Thin Dew Irrigation in Pinghu City (Single Crop Rice)

Irrigation method	Upper and lower limit of irrigation	Seedling stage	early tillering stage	late tillering stage	jointing and booting stage	heading and flowering stage	milk maturity	yellow maturity
Rainwater storage and thin dew irrigation	Lower limit of irrigation	5	Microfracture of field surface $0.8\theta_s$	Microfracture of field surface $0.7\theta_s$	Microfracture of field surface $0.9\theta_s$	0	Microfracture of field surface $0.8\theta_s$	Natural desiccation
	Upper irrigation limit	20	20	20	30	30	20	
	Upper limit of rain storage	50	80	0	140	120	80	

Note: θ_s stands for field water holding capacity

The rice in the experimental field of Pinghu Irrigation Test Station is planted by direct seeding. It will be soaked in the field from June 10 to 13, 2021, sown on June 14, and yellow in November 5. The growth period is 145 days. Irrigation in rice growing period is basically implemented according to the upper limit of irrigation in Table 1, and the height of the upper gate at the drainage outlet is implemented according to the upper limit of rain storage. According to the irrigation and drainage observation records of the test station on the four test fields (Table 2), the irrigation volume of the farmland in the Honda period is 307.5 mm-368.5 mm, or 205.1 m^3-245.8 m^3, which is 76% - 91% of the thin open irrigation quota under the 75% guarantee rate of Zhejiang Province, and the effective utilization rate of rainwater reaches 64.1% and 66.4%. After paddy field irrigation, the water is accompanied by inorganic nitrogen, pesticides and other substances, which generally settle at the bottom of paddy field after standing. During drainage, the water flow starts from the surface of the gate, and the discharged water is mainly clear water after sedimentation. The sludge and small rocks in the field are blocked in the gate, which not only prevent the nutrients required by crops and water and soil loss, but also reduce the accumulation of sludge in drainage ditches and river channels, and also reduce the pollution of the river course, which is conducive to environmental protection. Through the promotion and application in the rice growing period of Pinghu City in 2021, the paddy field precision irrigation and drainage control equipment has fully played the role of rain storage, water saving, emission reduction, peak shaving, etc., and has achieved significant comprehensive effect of water saving and emission reduction, which has been unanimously praised by growers, water drafters and agricultural technicians. According to the calculation, Pinghu City will apply the paddy field precision irrigation and drainage control device in 2021. Compared with 2020, the irrigation power consumption in the same period will decrease by 268000 kWh, saving 5.7% electricity, and the irrigation water consumption will decrease by about 9.38 million m^3.

Table 2 Rice Irrigation and Drainage Observation Records of Pinghu Irrigation Test Station

Field	Irrigation times	Irrigation water volume /mm		Rainfall /mm	Effective rainfall /mm	Rainfall utilization rate /%	Water discharge /mm
		Total water volume	Irrigation water volume in growing period				
NO.1	8	401.2	307.5	924	592.5	64.1	384.6
NO.2	8	461.9	368.5	924	592.5	64.1	384.5
NO.3	8	460	367.8	924	613.7	66.4	365
NO.4	8	455	361.7	924	592.5	64.1	385

Note: The field area is 1 mu(666.7 m^2)

4. Conclusion

Precision irrigation and drainage control of paddy fields is a key link to prevent and control non-point source pollution of paddy fields. It can play a role in rain storage, water saving, emission reduction, peak shaving, etc., and significantly reduce the impact of non-point source pollution on water bodies. The automatic precision irrigation and drainage system for farmland with low environmental impact designed in this paper is advanced and practical. In combination with the promotion of water-saving irrigation technology for rice and the transformation of seepage prevention and leakage prevention for rice fields, it can not only improve the efficiency of water and fertilizer utilization during rice production, with significant economic benefits, but also produce significant environmental benefits through effective prevention and control of agricultural non-point source pollution, which is worth extensive promotion and application in rice planting.

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RESEARCH AND APPLICATION OF A NEW PRECISION IRRIGATION AND DRAINAGE CONTROL DEVICE FOR PADDY FIELD

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ABSTRACT

Extensive irrigation and drainage management of paddy field leads to serious loss of water and fertilizer, low utilization rate and water environmental pollution in the plain river network region in Southern China. This paper studies a new type of paddy field precision irrigation and drainage control device, which can accurately control the water layer depth of paddy field through double gate adjustment, effectively use rainwater and control drainage, reduce nitrogen and phosphorus loss of paddy field, have obvious effects of rain storage, water saving and emission reduction, simple structure, simple operation and low cost, and have good popularization value.

Keywords: Paddy field; Rice; Irrigation; Drainage; Device

1. Introduction

The rice planting area in southern China is large. Due to the imperfect functions of storage and drainage facilities in rice fields and unreasonable irrigation, fertilization and drainage, the water quality in southern China is short of water. Taking Zhejiang Province of China as an example, according to the Second National Pollution Source Census Bulletin of Zhejiang Province, in 2017, among the agricultural source water pollutant emissions in Zhejiang Province, the planting industry pollution emissions accounted for 71.2%, total nitrogen 84%, and total phosphorus 81.3%. The research on water saving, fertilizer control and pollution reduction technologies in rice production is extremely urgent. We should actively explore and apply reasonable farmland management methods, improve agricultural water conservancy facilities, increase the utilization rate of chemical fertilizers, and prevent the loss of pollution. The precision irrigation and drainage management and control technology of paddy field keeps the fertilizer in the farmland ecosystem as much as possible by precisely controlling the irrigation and drainage volume of paddy field, reducing the discharge of agricultural non-point source pollutants, improving the rural water environment and ensuring that the rice yield does not decrease. Therefore, under this situation, this paper has studied a simple, practical and easy to operate rice field precision irrigation and drainage control device to achieve precision drainage and irrigation of rice fields, which is of great practical significance for agricultural water conservation and emission reduction and agricultural non-point source pollution control in southern rice growing areas.

2. Current main methods of paddy field irrigation and drainage

The survey found that the paddy field irrigation and drainage generally adopts the forms of simple board type small sluice irrigation and drainage, buried pipeline irrigation and drainage, and direct ridge excavation irrigation and drainage. During irrigation and drainage of rice fields, the water drainer needs to frequently adjust the outfall according to his experience to maintain a proper water layer on the field surface. The amount of field work is large, and in case of heavy rain, it is easy to cause the rice to be flooded or the outfall to collapse, leading to the loss of water and fertilizer. It is difficult to use rainwater effectively.

3. New control method for precision irrigation and drainage of paddy field

In combination with the application of water-saving irrigation technology for rice in the southern plain river network area, a new type of paddy field precision irrigation and drainage control device is designed, which is mainly composed of a box, a chute, a scale, upper and lower rams, and a handle. See Figure 1 for details. For rice planting in rainy areas in the south, the device can accurately control the irrigation water layer by using the overflow mode at the top of the gate according to the water demand at different growth stages of the rice growth period. At the same time, according to the submergence tolerance depth of rice in different growth stages, rainwater can be stored to reduce water intake in the river channel, which can not only effectively retain rainwater, but also avoid rice yield reduction caused by excessive flooding, so as to achieve accurate control of the water

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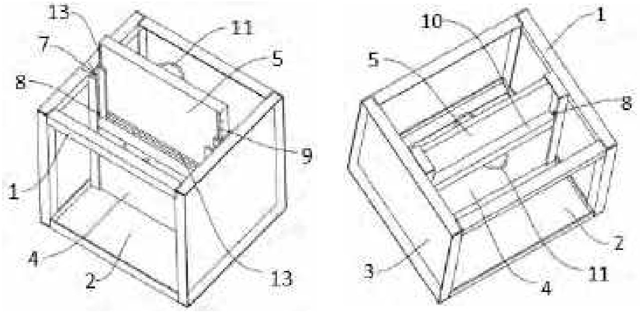
layer in the rice field. For dry land crops in winter, the device realizes bottom drainage and discharges waterlogged water by adjusting the ram.



1. Framework; 2. Base plate; 3. Side plate; 4. Low level plate; 5. High level plate; 6. Chute; 7. Movable trough; 8. Limit column; 9. Limit hole; 10. Beam; 11. Handle; 12. The first sealing strip; 13. Second sealing strip

Figure 1 Design Diagram of Paddy Field Precision Irrigation and Drainage Control Device

4. Design of Precision Irrigation and Drainage Control Device for Paddy Fields

4.1 Device structure

The double ram overflow type paddy field precision irrigation and drainage control device is designed as a box structure. The box is composed of a bottom plate, left and right side plates, and upper front and rear support beams. The middle of the left and right side plates is provided with upper and lower through chutes. A cross beam is set at half the height of the spacing belt in the middle of the chute, and a scale is set at the spacing belt in the middle of the chute based on the top surface of the cross beam. A ram is installed at the upper and lower sides of the chute on both sides of the beam. The height of the ram is half of the height of the box. The device is provided with a rectangular frame, which can also be set into a cubic structure. In actual use, the specific shape and size of the frame can be set according to the size of the paddy field. The frame and related parts can be made of glass fiber reinforced plastic or angle iron and other materials during actual manufacturing, which can ensure the structural strength and stability of the device and is conducive to long-term use. The setting of bottom plate and side plate is conducive to the overall stability of the frame, and can also ensure that the water is discharged through the frame to avoid water loss around the frame. Moreover, the setting of bottom plate is also convenient for the installation of two rams.

Two rams are set in parallel. The two rams are located between the two side rams. Each ram can move up or down. When the two rams move up and down, water flows out through the frame. The two rams are set as low level rams and high level rams, and the water flows outward from one side of the low level rams to the other side of the high level rams. The height of each ram is lower than the height of the side plate, and the height of each ram is greater than half of the height of the side plate. The opposite side of the two side plates are respectively installed with vertically arranged chutes. The two sides of the ram are respectively embedded in the two chutes. Two limit posts corresponding to the two rams are fixed in the chute. A row of limit holes corresponding to the limit posts are symmetrically arranged on both sides of each ram. The two rams fit each other, and the top of each ram is covered with the first sealing strip. Separate plates are respectively fixed in the two chutes, which divide the chute into two movable chutes. The two rams are respectively located in the corresponding movable chutes, and each movable chute is fixed with a limit column. The opposite sides of the two rams are respectively provided with a plurality of second sealing strips. A handle is arranged on the ram, which can be arranged on the top or side of the ram to facilitate the operator to exert force on the ram. Servo motor and screw can also be set on the frame to control the up and down movement of the ram, or even remotely control the servo motor through electronic equipment to further improve the purpose of automatic control production.

4.2 Installation and use of devices

The irrigation and drainage control device is installed on the ridge between the paddy field and the drainage ditch or the farmland drainage pipe is close to the farmland side. When installing, the top surface of the beam is flush with the farmland surface, and the bottom plate of the box is slightly lower than the bottom of the dry crop field ditch. The box height and ram height of the irrigation and drainage control device should fully consider the local dry season crop drainage requirements. The lower ram height should be greater than the dry season crop field drainage ditch depth. It is recommended that the height of the irrigation and drainage control device be 40cm - 50cm. Before installation, the direction of the drainage gate shall be distinguished. The high lift gate is located at the paddy field side, and the low lift gate is located at the drainage channel side. During field installation, first dig a narrow trapezoidal groove with upper width and lower width at the proper position of the ridge, and the bottom is slightly wider than the width of the irrigation and drainage control device. Then lay a layer of clay and quicklime to mix evenly. After the irrigation and drainage control device is positioned, compact and calibrate the elevation. Then fill and compact the two sides of the side plate with clay and quicklime mixture layer by layer, or replace the mixture with cement mortar.

The design of double ram overflow type paddy field precision irrigation and drainage control device fully considers the rice dry rotation mode in southern China. During the rice growing season, the lower gate of the irrigation and drainage control device is pressed to the bottom plate to retain water, and the upper gate is adjusted according to the submergence tolerance depth of rice in different growth periods according to the scale on the chute to retain irrigation water. At the same time, the reservoir capacity between the set irrigation depth and the submergence tolerance depth of rice can be used to store rainfall. When excessive irrigation or rainstorm occurs, the excess water exceeding the submergence tolerance depth overflows from the top of the upper gate to the drainage ditch. During the growing season of dry crops, the upper and lower rams are all lifted to the upper part, and the field waterlogged water is drained to the drainage ditch through the bottom plate of the irrigation and drainage control device.

During normal drainage (usually due to too much water in the paddy field), if the water is drained from below the low level plate, the water flow will have a greater impact under the influence of gravity, which will easily affect the roots of crops. Therefore, during normal drainage, the head board is directly controlled to move downward, and the water flow is discharged from above the head board, so that the water stored in the paddy field is gradually discharged from top to bottom, and the water flow is relatively gentle, thus ensuring the stable growth of crops.

5. Application

The double ram overflow type paddy field precision irrigation and drainage control device was applied in Pinghu Irrigation Test Station and Huoluobang Irrigation District of Zhejiang Province in 2021. Four treatments were arranged in the irrigation test station, and the field surface conditions were consistent with the paddy fields in the surrounding irrigation areas. Four sets of double ram overflow type paddy field precision irrigation and drainage control devices were used, each with a control area of 667m^2, for manual observation. The irrigation area of Huoluobang Irrigation Area is 550 mu, including 350 mu of rice. A field is selected as the observation area, with an area of 1000m^2, and the soil moisture monitor is used for observation. The rice planting in Pinghu City, Zhejiang Province is dominated by single cropping rice. The growing season in 2021 is from June to November. The method of rice rain storage and thin dew irrigation is adopted. Thin dew irrigation is a kind of irrigation technology for rice to irrigate thin water layer and timely dry open field. In order to improve the utilization rate of rainwater, Pinghu City has formulated the field water layer control standard for rain storage thin exposed irrigation. See Table 1 for details.

Table 1 Field Water Layer Control Standards for Rainfall Storage and Thin Dew Irrigation i n Pinghu City (Single Crop Rice)

Irrigation method	Upper and lower limit of irrigation	Seedling stage	early tillering stage	late tillering stage	jointing and booting stage	heading and flowering stage	milk maturity	yellow maturity
Rainwater storage and thin dew irrigation	Lower limit of irrigation	5	Microfracture of field surface 0.8θ_s	Microfracture of field surface 0.7θ_s	Microfracture of field surface 0.9θ_s	0	Microfracture of field surface 0.8θ_s	Natural desiccation
	Upper irrigation limit	20	20	20	30	30	20	
	Upper limit of rain storage	50	80	0	140	120	80	

Note: θ_s stands for field water holding capacity

The rice in the experimental field of Pinghu Irrigation Test Station is planted by direct seeding. It will be soaked in the field from June 10 to 13, 2021, sown on June 14, and yellow in November 5. The growth period is 145 days. Irrigation in rice growing period is basically implemented according to the upper limit of irrigation in Table 1, and the height of the upper gate at the drainage outlet is implemented according to the upper limit of rain storage. According to the observation records of irrigation and drainage in the test field, the irrigation volume of farmland in the Honda period is 307.5 mm-368.5 mm, or 205.1 m^3-245.8 m^3, which is 76% - 91% of the thin and exposed irrigation quota under 75% assurance rate in Zhejiang Province. The effective utilization rate of rainwater reaches 64.1% and 66.4%. The double gate overflow drain has obvious effects on rainwater storage, water saving and emission reduction.

The rice planting in the experimental field of Huoluobang Irrigation Area adopts the method of machine transplanting. The rice is transplanted on June 20, the rice is yellow on October 30, and the paddy field lasts 133 days. The irrigation in the paddy field is basically carried out according to the upper limit of irrigation in Table 1, and the height of the upper gate at the drainage outlet is carried out according to the upper limit of rain storage. According to the monitoring data of the soil moisture monitor, there were 8 times of irrigation in Honda period, with 291.38 cubic meters of water used, which was 108% of the quota of thin dew irrigation under 75% guarantee rate in Zhejiang Province, slightly higher than the quota standard.

6. Conclusion

The existing paddy fields often have water inlets and drainage outlets on the ridge for irrigation and drainage, but the effect of such irrigation and drainage is not ideal, the depth of the water layer can not be accurately controlled and timely drainage can not be achieved, and the drainage volume can not be accurately controlled. For the crops planted, the water required at different growth stages is different, which further increases the difficulty of water control.

Compared with the prior art, the structure of the double ram overflow type paddy field precision irrigation and drainage control device is reasonable, and the drainage is controlled through the setting of two rams, which is simple to operate; By controlling the position change of the ram, the purpose of precise control and complete drainage of the farmland water layer can be achieved, and the use effect is good. The device adopts the overflow drainage mode at the top of the gate during the rice growing period, which changes the bottom drainage mode of the traditional drainage device and effectively prevents the soil erosion on the field surface. At the same time, because the nitrogen and phosphorus concentrations in the surface water of the rice field increase from top to bottom with the depth of the water on the field surface, under the condition of rain storage in the rice field, the overflow drainage at the top of the gate can reduce the nitrogen and phosphorus loss in the farmland and reduce the pollution load of the river channel. By controlling the depth of rainwater storage in paddy fields, rainwater can be intercepted, runoff can be reduced, flood peak can be reduced, and operation efficiency of plain river network and polder area can be improved. Moreover, the device has the advantages of small investment, convenient maintenance and management, low maintenance cost, etc.

On the premise that the economic cost is controllable, the irrigation and drainage control device can subsequently consider adding remote automatic control function or water level monitoring function. Through linkage with the water inlet, it can achieve automatic precision irrigation and improve the digital level of farmland drainage management.

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EFFECTS OF WATER SAVING AND DRAINAGE REDUCTION PRACTICES ON HUOLUOBANG IRRIGATION DISTRICT IN THE PLAIN RIVER NETWORK REGION IN SOUTHERN CHINA

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ABSTRACT

In order to save water and reduce drainage from paddy fields, the huoluobang irrigation district, located in the river network district of the southern plain of China, has implemented water-saving transformation, improved the water management level, adopted the single season rice rain storage and thin dew irrigation technology, and built a comprehensive emission reduction system consisting of fields, ecological ditches, ponds and wetlands. The two-year observation results show that the total water consumption in huoluobang irrigation district has been effectively controlled, and the water and electricity saving effect is obvious. Compared with the control year, the water consumption is 33% and 23% respectively, and the electricity consumption is 45% and 22% respectively; The ecological ditches and ponds in the irrigation district can effectively intercept rainfall runoff and paddy field drainage. By using the physical, chemical and biological mechanisms in the wetland ecosystem, the concentration of nutrients in the water is significantly reduced. The comprehensive emission reductions of permanganate index, total phosphorus and total nitrogen are 39.7%, 41.9% and 17.2% respectively.

Keywords: Paddy field; Irrigation district; Water saving; Drainage reduction

1. Introduction

Problems such as extensive management, low water use efficiency and serious non-point source pollution discharge are common in rice water use, which are difficult and weak links in water resource management and water pollution prevention. The traditional way of irrigation and fertilization is extensive, and the utilization rate of water and fertilizer is low, leading to the increasing proportion of non-point source pollutants into the river in rice production, which has become one of the main sources of agricultural non-point source pollution in the river network area of the southern plain.

According to the generation, migration and transformation mechanism of agricultural non-point source pollution in the southern plain river network area, the prevention and control of agricultural non-point source pollution can be started from two aspects: source control and process reduction. In the aspect of source control, such as the use of water-saving irrigation, controlled drainage and other field irrigation and drainage technologies to control non-point source pollution; During transportation, conduct resistance control, interception and reduction. Compared with the two, source control is more important. As an important management measure to reduce the discharge of non-point source pollutants from the source, water-saving irrigation in rice fields can reduce the amount of irrigation water in different growth periods, thereby reducing the amount of drainage and sewage discharge to reduce the non-point source pollution in farmland.

2. Basic information of irrigation area

Huoluobang Irrigation District is located in Shenjianong Village, Zhongdai Street, north of Pinghu City, Zhejiang Province. Shenjianong Village borders Zhongnan Village in the south, Huimin Town, Jiashan County in the north, Shanghaitang in the east and Zhongdai Community in the west. The transportation in the irrigation district is convenient. The irrigation area belongs to the subtropical monsoon climate zone, with an average annual temperature of 15.7 ℃, an average annual rainfall of 1252 mm, and an average annual sunshine duration of 2075 h. The soil is mainly silty clay, and the parent material of soil formation is offshore sediment, with a unit weight of 1.3-1.4 g cm^{-3}.

The designed irrigation area of Huoluobang Irrigation Area is 550 mu, which is divided into two blocks in the north and south. The irrigation area of Block I (the north block) is 245 mu, including 210 mu of rice and 35 mu of seedlings and other crops; Block II (south block) has an irrigation area of 305 mu, including 200 mu of rice and

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105 mu of economic crops such as watermelon. Irrigation in the irrigation area is mainly carried out by pumping station from the river channel, and water is delivered to Block I and Block II respectively through two main pipes. The branch pipes are arranged perpendicular to the main pipes or sub main pipes, and most of the branch pipes discharge water from one side.

There is one irrigation pump station in Huoluobang Irrigation Area, which is located in the east of the irrigation area. Before the transformation, there are no supporting metering facilities; 5.11km low pressure irrigation pipeline has been built. After years of operation, the pipeline is damaged, blocked, and the water flow is not smooth, so it needs to be repaired again; The U-shaped drainage ditch is 2.77 km long, which can basically meet the drainage requirements of the irrigation area. Local ditch sections are damaged and the drainage is not smooth, so it needs to be removed and rebuilt. In recent years, due to the increase in the use of pesticides and fertilizers, agricultural non-point source pollution in irrigation areas is severe, and the water quality is relatively poor, which needs to be improved.

The Huoluobang Irrigation Area is surrounded by rivers on three sides. It is a typical river network pumping irrigation area in the Hangjiahu Plain. It is representative of the Hangjiahu River Network Plain in terms of scale, crop type, engineering facilities, and management status, and the boundary is relatively clear, facilitating the monitoring and evaluation of implementation effects.

Figure.1 Layout Plan of Irrigation Area Project

3. Water saving and emission reduction facility system

3.1 Construction objectives

According to the concept of "standardization, informatization and ecology", through the construction of four systems, namely "modern irrigation and drainage engineering system", "comprehensive emission reduction system of agricultural non-point sources", "three red lines" monitoring system for agricultural water use "and" standardized management system for irrigation areas ", Huoluobang Irrigation Area will be built into a" modern green "demonstration irrigation area with" complete facilities, efficient water use, standardized management, good ecology and beautiful environment ".

3.2 Facility system

(1) Modern irrigation and drainage engineering system

Irrigation project reconstruction: in order to achieve efficient water-saving irrigation, the old and worn concrete pipe is replaced by PE pipe, and the total field irrigation pipe is 5912 m. A frequency conversion energy-saving control cabinet is installed in the pump station to control the original two pumps in the pump station.

Drainage ditch reconstruction: on the premise of meeting the basic functions of drainage, the traditional hard drainage ditch shall be reconstructed according to the concept of "ecological". In Block I, a 520 m ecological ditch has been built, where a variety of aquatic cash crops have been planted, such as canna, water bamboo, lotus, etc.

River regulation: In combination with the original ecological plant conditions of the river, the river course 480 m north of the irrigation area will be "ecologically" renovated to build a pond wetland. The riverway bank slope is mainly reinforced by pine piles, and floating beds are set on the riverway.

(2) Comprehensive emission reduction system of agricultural non-point sources

The comprehensive emission reduction system of agricultural non-point source in the irrigation area aims at efficient utilization of water and fertilizer, water conservation, efficiency increase and pollution reduction. The single cropping rice rain storage and thin dew irrigation technology is used to reduce the emission of nitrogen, phosphorus and other pollutants from the source. At the same time, the ecological ditch and wetland system are constructed to form the three lines of defense for pollution prevention, reduction and treatment in the irrigation area.

Source control defense line: Promote the single cropping rice rain storage thin exposed irrigation technology and water fertilizer coupling technology that have been tested and studied by Pinghu Experimental Station for many years, and reduce agricultural non-point source pollution emissions from the source.

Ecological ditch defense line: in combination with drainage ditch reconstruction and plant measures (canna, water bamboo, lotus, etc.), ecological ditches are constructed to absorb nitrogen, phosphorus and other pollutants in paddy field drainage through reasonable hydraulic control of water retention time.

Pond wetland defense line: use the existing pond near the block I main drainage outlet to build a natural wetland system, and further reduce the non-point source pollution discharge in the irrigation area through reasonable hydraulic regulation and appropriate vegetation measures.

(3) "Three Red Lines" Monitoring System for Agricultural Water Use

In accordance with the requirements of the strictest water resources management system for agricultural water management, the "three red lines" monitoring and evaluation system is established in the irrigation area.

Dynamic monitoring of water volume: one electromagnetic flowmeter and one ultrasonic flowmeter are installed on the two main outlet pipes at the head of the pump station to monitor the total amount of irrigation water; Select 6 typical fields in Block I to install 6 field water meters to monitor the gross irrigation water consumption in the field; One water measuring facility is arranged at the outlet of the ecological ditch in the irrigation area to monitor the water discharge in the north of the irrigation area.

Regular water quality inspection: 20 water quality sampling points are set at the pump station inlet, field, U-shaped channel outlet, ecological ditch, pond wetland, control field and control ditch, and the sampling water quality is inspected.

Information construction: introduce modern information control technology, realize remote automatic opening and closing of pump station, configure automatic irrigation control system in irrigation area, and realize automatic irrigation and remote data transmission in irrigation area through supporting software and hardware.

(4) Standardized management system of irrigation area

With the goal of realizing standardized management, the standardized management system of irrigation district is explored in the aspects of project management and maintenance, water management, incentive mechanism, etc.

Project management and maintenance: including daily patrol and regular inspection by management personnel. The focus of daily inspection is to check and record the potential hazards, defects, man-made damage, damage, etc. that may exist in the irrigation area; Regular inspection is mainly to regularly check and record the pump station, electromagnetic flowmeter, ultrasonic water level gauge, water meter, etc.

Water management: village level management mode is adopted. Shenjialong Village Committee, as the management unit of the irrigation area, receives the technical guidance of Pinghu Water Conservancy Bureau, and in combination with the standardized management of the project, sets up a water discharger to be responsible for the operation and management of the pump station, and also serves as a water discharger and water sample sampler to be responsible for the drainage and water management of the rice block. Shenjialong Village Committee is responsible for the supervision of the work.

Incentive mechanism: The incentive mechanism is divided into two levels. The first is to encourage the village committee, which is mainly reflected in the maintenance funds; The second is to encourage water managers, which is mainly reflected in the bonus. According to the actual work situation of water releasers, appropriate rewards will be given to them to improve their enthusiasm.

3.3 Water saving and emission reduction monitoring scheme

3.3.1 Water volume monitoring

(1) Monitoring purpose

The purpose of irrigation water monitoring: to realize the dynamic monitoring and evaluation of the total water use and water efficiency in the irrigation area, master the real-time water use situation in the irrigation area, and provide the basis for the total agricultural water use control, quota management, efficiency evaluation, etc. in the irrigation area.

The purpose of drainage monitoring is to dynamically monitor the drainage of ecological ditches in irrigation areas, master the drainage of ecological ditches, and provide a basis for the evaluation of the effect of agricultural non-point source pollution reduction in irrigation areas.

(2) Monitoring position

Monitoring location of irrigation water: on the two main outlet pipes at the head of the pump station and at the water inlets of six typical fields in the block.

Drainage monitoring location: the outlet at the end of the ecological ditch.

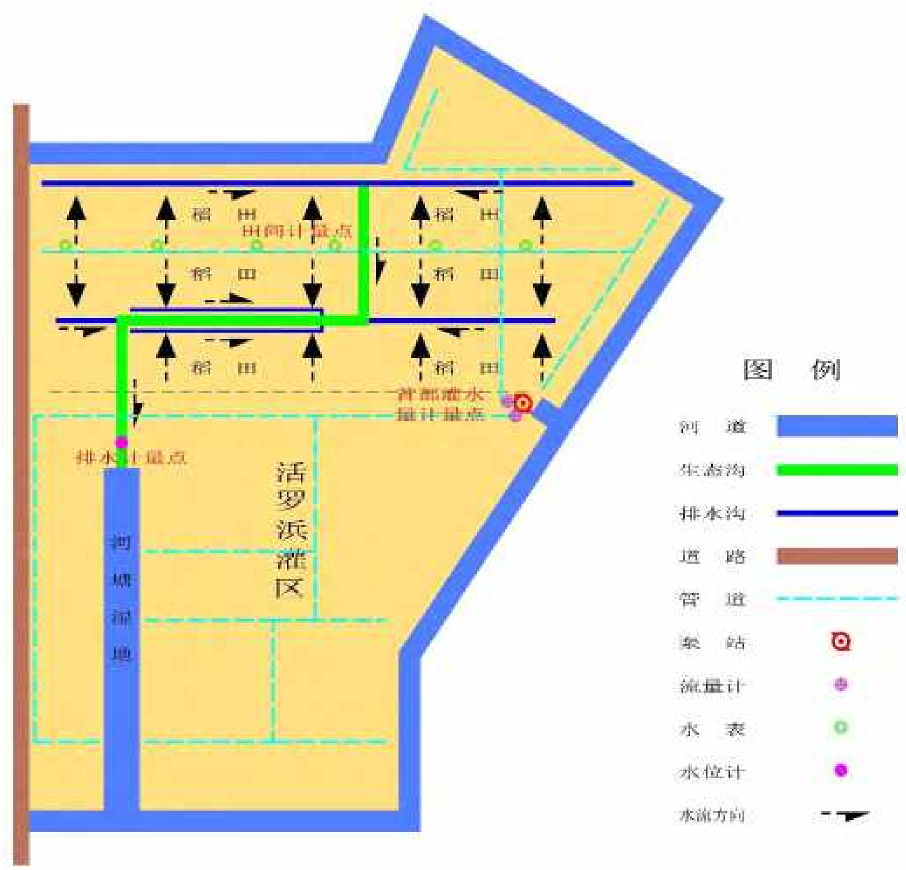

Figure.2 Layout of Water Monitoring Points

(3) Monitoring facilities

Irrigation water monitoring facilities: one DN500 electromagnetic flowmeter, one DN500 ultrasonic flowmeter and six DN65 field water meters.

Drainage monitoring facilities: a simple water sill type open channel flow real-time measuring device is used, namely, a simple water sill and an ultrasonic water level gauge. When there is no obvious drainage in the paddy field, the water collected into the ecological ditch by means of lateral seepage will be automatically stored in the ecological ditch, and the drainage gate at the outlet of the ecological ditch will be closed. The retention time of the water flow should be 3 to 4 days. Then open the drainage gate, and the water level will automatically drop to the top elevation of the measuring sill; When there is a small amount of drainage in the paddy field, after the paddy field is drained to the ecological ditch, close the drain gate. The retention time of water flow should be 3-4 days. Then open the drain gate, and the water level will automatically drop to the top elevation of the measuring sill; When there is large drainage in the paddy field, open the drainage gate in advance to drain the water level of the ecological ditch to the top elevation of the measuring bucket, and drain the water in the storage field to the upper limit of the control water level, and the excess part will automatically overflow to the pond wetland.

(4) Monitoring frequency

Monitoring frequency of irrigation water: real-time monitoring for the first part, and remote transmission of data for water volume; Real time monitoring in the field, recording data at the beginning of each irrigation.

Drainage monitoring frequency: real-time monitoring and remote transmission of water volume data.

3.3.2 Water quality monitoring

(1) Monitoring purpose
Analyze the water quality changes of fields, ecological ditches and ponds in irrigation areas, and provide a basis for the evaluation of agricultural non-point source emission reduction effect in irrigation areas.

(2) Monitoring indicators

Concentration of total phosphorus, total nitrogen, ammonia nitrogen, nitrate nitrogen and permanganate index.

(3) Layout of monitoring points

The drainage in the north of the project area (about 187 mu) is mainly through the field U-shaped canal, gathered in the ecological ditch, and finally flows into the pond wetland in the southwest of the project area; The drainage of other blocks in the project area is discharged into the surrounding river after passing through the field U-shaped channel.

One water quality monitoring point (1 #) is set at the water inlet of the pump station in the irrigation area; Set two water quality monitoring points (2 #, 9 #) in the field; Seven water quality monitoring points are set at the upstream (4 #), midstream (5 #, 7 #, 8 #, 13 #, 14 #) and downstream (15 #) of the ecological ditch to detect the change of drainage water quality, and five water quality monitoring points (3 #, 6 #, 10 #, 11 #, 12 #) are set at the inlet of each drainage point of the ecological ditch; Two water quality monitoring points (16 # and 17 #) are set up at the upstream and downstream of the pond wetland in the north of the irrigation area to monitor the water quality changes of river water after being purified by ecological measures such as ecological bank protection and aquatic plants. The layout of water quality monitoring points is shown in Figure 2-11.

(4) Monitoring methods

Collect 500 mL of water sample at the water quality monitoring point, then add 2 mL of acid stabilizer (5N HCl) and label it.

(5) Monitoring frequency

Take water samples from 1 #~20 # fixed points of the ecological ditch for testing in turn, and take samples every 7 days or so.

4. Analysis on the effect of water saving and emission reduction

4.1 Water saving effect analysis

4.1.1 Analysis of irrigation water consumption

The crops in Woluobang Irrigation Area include rice (single cropping rice), dry crops (wheat, rape), etc. Rice is the main irrigation crop in the irrigation area, and its growth period is generally from June to October. According to its growth process, it can be divided into seven stages: soaking period, green returning period, tillering period (early and late tillering), jointing and booting period, heading and flowering period, milk maturity period, and yellow maturity period. Dry crops (wheat, rape) are generally rotated with rice. The growth period is generally from

December to May of the next year. The maximum water demand occurs in April, with an average of 3.5~4.0 mm/d, and the water demand during the growth period is 300~480 mm. However, due to the abundant rainfall in Pinghu area, irrigation is basically not required in general years, and only a small amount of irrigation is required in dry years. See Table 1 for water use at each growth stage of rice.

It can be seen from Table 1 that the average gross irrigation water consumption per mu during the whole rice growth period (including soaking period) in 2016 and 2017 was 849 m3 and 982 m3 respectively. The period with more irrigation water consumption is the tillering stage and jointing booting stage, accounting for 56% and 64% of the total water consumption in 2016 and 2017 respectively. The period with more daily average irrigation water consumption is mainly in the tillering stage and jointing booting stage.

Table 1 Summary of Irrigation Water Consumption at Each Growth Stage of Rice

NO.	Stage		Start date	Days /d	Gross irrigation water consumption $/m^3mu^{-1}$	
					2016	2017
1	Potting period		6.17～6.21	5	100.9	131.9
2	Rejuvenated period		6.22～6.29	8	65.7	37.9
3	Tillering stage	Early tillering stage	6.30～7.19	20	90.0	269.5
		Later tillering stage	7.20～8.3	15	156.1	216.9
4	Jointing booting stage		8.4～8.26	25	227.6	141.3
5	Heading and flowering stage		8.27～9.4	9	112.2	66.8
6	Milk ripening stage		9.5～9.22	18	32.5	117.42
7	stage of yellow ripeness		9.23～11.5	44	64.1	0
Total			6.17～11.5	144	849.1	981.8

4.1.2 Water saving effect analysis

In 2016 and 2017, the average gross irrigation water per mu in Woluobang Irrigation District was 849 m^3 and 982 m^3 respectively. The water utilization coefficient of the pipeline was 0.95, and the calculated water consumption for rice field irrigation was 806 $m^3 mu^{-1}$ and 933 $m^3 mu^{-1}$ respectively. Compared with the irrigation water quota, there is still much room for improvement. However, compared with the irrigation water consumption of the irrigation area in previous years (calculated according to the relationship between the actual irrigation water consumption and power consumption in the irrigation area in recent two years, the hydropower coefficient is 41.9 $m^3\ kW^{-1}\ h^{-1}$, the average power consumption in the irrigation area in previous years is 16646 kW • h, and the average gross irrigation water consumption in the irrigation area is about 1268 $m^3 mu^{-1}$), which has been greatly improved, with 33% and 23% water saving respectively. It can be seen that the water saving effect in Huoluobang Irrigation District is obvious through the promotion of single season rice rain storage and thin dew irrigation technology.

4.2 Analysis of emission reduction effect

4.2.1 Field emission reduction effect analysis

(1) Analysis of field drainage

During the growth of rice, field drainage is mainly controlled by two factors. One is seasonal drainage for rice growth, that is, field drainage or field drying according to the needs of rice physiological growth. Generally speaking, the seasonal drainage of rice growth mainly occurs in the green returning period of rice. After rice filling, several "running water" conducted in the field can also be regarded as the seasonal drainage of rice growth. The other is forced field drainage due to excessive rainfall, that is, passive field drainage due to concentrated rainfall or rainstorm during rice growth.

According to the monitoring data statistics of ultrasonic water level gauge at the end of the ecological ditch, the rice has different degrees of drainage at each growth stage. See Table 3-2 for specific drainage at each stage.

Table 2 Summary of Water Discharge at Each Growth Stage of Rice

NO.	Stage		Start date	Days /d	water discharge /mm	
					2016	2017
2	Rejuvenated period		6.22～6.29	8	45.4	35.3
3	Tillering stage	Early tillering stage	6.30～7.19	20	54.4	70.0
		Later tillering stage	7.20～8.3	15	47.9	92.1
4	Jointing booting stage		8.4～8.26	25	130.9	170.0
5	Heading and flowering stage		8.27～9.4	9	58.0	96.0
6	Milk ripening stage		9.5～9.22	18	151.8	115.9
7	stage of yellow ripeness		9.23～11.5	44	178.0	102.6
Total			6.22～11.5	139	666.4	681.9

In 2016 and 2017, the drainage volume was 666.4 mm and 681.9 mm respectively, which was mainly concentrated in rice jointing booting stage, milk ripening stage and yellow ripening stage, accounting for more than 56% of the total drainage volume. See Fig. 3 and Fig. 4 for paddy field drainage and rainfall

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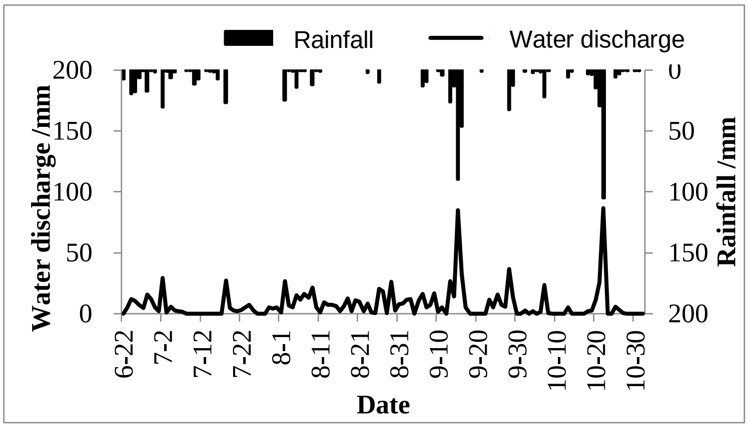

Figure 3 Rice field drainage and rainfall in 2016

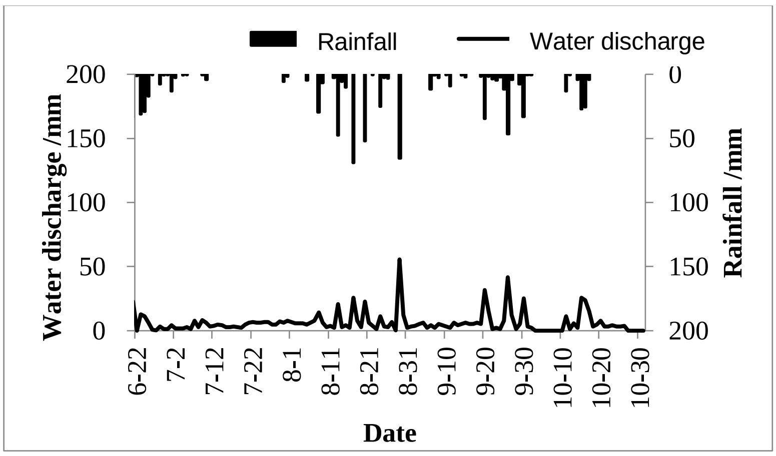

Figure 4 Paddy field drainage and rainfall in 2017

As shown in Figure 3 and Figure 4, the peak period of rainfall is also the peak period of paddy field drainage. For example, in the middle of September and late October 2016, as well as in August and late September 2017, there is obvious drainage. In addition, in rice tillering stage and jointing booting stage, the frequency of paddy field drainage is relatively high. During this period, the paddy field has continuous irrigation, which is discharged due to surface drainage, paddy field leakage and other reasons. At the same time, nitrogen, phosphorus and other substances not absorbed and utilized by crops will also enter the ecological ditch along with the drainage of rice fields.

(2) Change of pollutant concentration in the field

Due to the application of chemical fertilizer in the field and the absorption and utilization of nitrogen, phosphorus and other substances by rice plants, the concentration of various pollutants in the field changes at different times. The concentration of each pollutant increased significantly after the early field fertilization. In the later stage, with the cessation of fertilization and the further absorption and utilization of nitrogen, phosphorus and other substances by rice plants, the concentration of each pollutant gradually decreased. After the heading and flowering stage of rice, the concentration fluctuated relatively small.

(3) Analysis of field emission reduction

The field emission reduction is analyzed by the emission reduction rate. The calculation formula of the emission reduction rate is:

$$\eta = \frac{\sum q_{in} - \sum q_{out}}{\sum q_{in}} \qquad (1)$$

$$q_{out} = Qc \qquad (2)$$

Where η is emission reduction rate, q_{in} is weight of material inflow per unit area, q_{out} is weight of material inflow per unit area, Q is water discharge, c is substance concentration in drainage.

A positive value means that the total inflow of substances is greater than the total outflow of substances, and the total amount of pollutants increases; Negative value means that the total inflow of substances is less than the total outflow of substances, and the total amount of pollutants decreases; Zero means there is no inflow (outflow) during this period.

Surface water pollutants are one of the main ways to generate non-point source pollution. Especially after a large amount of rainfall, the paddy field is forced to drain, bringing out nutrients such as nitrogen and phosphorus, pesticides and other organic or inorganic pollutants from the field, thus polluting the receiving water body. The paddy field itself is a small ecological wetland, which absorbs nutrients such as nitrogen and phosphorus from the field through plants, while the unabsorbed nutrients enter the ditch along with the drainage.

Permanganate index, ammonia nitrogen, total phosphorus and total nitrogen in the field decreased by 57.2%, 18.1%, 48.7% and 24.0% respectively, while nitrate nitrogen increased by 6.0%. The increase of nitrate nitrogen may be caused by the mutual transformation of ammonia nitrogen and nitrate nitrogen. In normal water bodies, the ammonia nitrogen content is generally less than nitrate nitrogen. Once there are two equal or high ammonia nitrogen content, or even higher than nitrate nitrogen, the water body may be polluted, and a large amount of organic nitrogen is discharged to cause this phenomenon. The content of ammonia nitrogen in the early stage is higher than that of nitrate nitrogen, and fertilization is mainly concentrated in the early stage, which indicates that fertilization affects the content of ammonia nitrogen and nitrate nitrogen in the field. However, the cessation of fertilization at any time in the late stage and the absorption and utilization of nitrogen in the paddy field lead to the gradual balance of ammonia nitrogen and nitrate nitrogen in the field.

To sum up, emission reduction in the field can be achieved through the following two ways: first, water-saving irrigation of rice, reducing irrigation water consumption, thereby reducing drainage, and ultimately achieving the goal of emission reduction; Second, the coupling technology of water and fertilizer, rationally use chemical fertilizers and pesticides, improve the utilization rate of chemical fertilizers and pesticides, and reduce pollutant emissions from the source. Through water-saving irrigation+water fertilizer coupling technology, the discharge of permanganate index, total phosphorus and total nitrogen at the source has been reduced in Huoluobang Irrigation District.

4.2.2 Comprehensive emission reduction effect analysis

The Huoluobang Irrigation Area has built a comprehensive emission reduction system through three lines of defense, namely, fields, ecological ditches and ponds and wetlands. The total emission reduction of various pollutants is shown in Table 3.

Table 3 Comprehensive Emission Reduction of Pollutants in Each Period g mu^{-1}

NO.	Period	Name	Permanganate Index	Ammonia Nitrogen	Total Phosphorus	Nitrate Nitrogen	Total Nitrogen
1	7/5～7/8	Inflow	919.2	97.7	12.4	30.4	203.1
		Outflow	670.1	90.0	9.7	40.8	259.4
		Difference	249.0	7.7	2.6	-10.4	-56.3
2	7/9～7/16	Inflow	1296.4	69.7	26.1	29.9	400.4
		Outflow	968.0	158.3	18.9	42.3	353.4
		Difference	328.4	-88.6	7.3	-12.4	47.0
3	7/17～7/23	Inflow	1447.7	43.7	22.6	34.7	212.3
		Outflow	1249.7	46.5	19.9	41.2	229.2
		Difference	198.1	-2.9	2.7	-6.6	-16.9
4	7/24～7/29	Inflow	1835.3	364.1	32.3	46.4	724.0
		Outflow	805.6	217.8	14.2	59.1	427.7
		Difference	1029.7	146.3	18.1	-12.7	296.4
5	7/30～8/5	Inflow	1663.2	37.1	21.8	37.6	273.2
		Outflow	649.4	27.3	11.1	51.8	135.7
		Difference	1013.8	9.8	10.7	-14.3	137.5
6	8/6～8/12	Inflow	633.2	38.7	16.1	73.9	170.1
		Outflow	581.7	37.0	14.0	63.7	170.3
		Difference	51.4	1.7	2.1	10.2	-0.2
7	8/13～8/19	Inflow	616.2	28.5	13.3	65.7	170.6
		Outflow	474.9	31.7	12.1	71.0	164.8
		Difference	141.2	-3.1	1.2	-5.3	5.8
8	8/20～8/25	Inflow	238.4	42.8	12.4	44.4	134.3
		Outflow	228.1	41.5	7.8	36.3	110.9
		Difference	10.3	1.4	4.6	8.1	23.4
9	8/26～8/30	Inflow	353.5	31.6	9.1	78.0	159.8
		Outflow	318.0	38.3	9.3	53.4	135.4
		Difference	35.5	-6.7	-0.2	24.6	24.4
10	8/31～9/3	Inflow	306.9	22.5	8.9	76.3	151.6
		Outflow	314.2	26.0	8.3	64.9	138.0
		Difference	-7.3	-3.6	0.6	11.4	13.6
11	9/4～9/9	Inflow	299.6	9.4	7.5	27.5	45.9
		Outflow	281.1	12.9	6.7	38.8	56.0
		Difference	18.4	-3.5	0.9	-11.3	-10.1
12	9/10～9/15	Inflow	4461.9	122.8	127.6	171.5	794.3
		Outflow	1571.2	52.9	42.5	255.2	539.6
		Difference	2890.8	69.9	85.1	-83.7	254.7
13	9/16～9/19	Inflow	235.0	14.2	7.9	47.7	69.9
		Outflow	247.9	14.1	7.0	36.0	55.1
		Difference	-12.9	0.0	0.9	11.6	14.8
14	9/20～9/30	Inflow	353.9	17.7	11.9	33.7	75.1
		Outflow	319.7	13.2	9.6	41.0	78.9
		Difference	34.2	4.6	2.4	-7.3	-3.8
15	10/1～10/15	Inflow	432.5	26.3	18.2	132.6	201.4
		Outflow	358.1	25.7	11.9	124.2	301.4
		Difference	74.4	0.6	6.2	8.4	-99.9
16	10/16～10/31	Inflow	217.8	18.9	7.2	89.3	137.1
		Outflow	197.4	4.4	3.5	1.2	92.2
		Difference	20.4	14.5	3.7	88.1	44.8
	Total	Inflow	15310.4	985.5	355.4	1019.4	3923.2
		Outflow	9235.1	837.5	206.4	1021.0	3248.0
		Difference	6075.4	148.1	148.9	-1.5	675.1

Through the construction of the comprehensive emission reduction system in the Huoluobang Irrigation District, the permanganate index, ammonia nitrogen, total phosphorus and total nitrogen emission reductions in the irrigation area were 6075.4 g mu^{-1}, 148.1 g mu^{-1}, 148.9 g mu^{-1} and 675.1 g mu^{-1}, respectively, down 39.7%, 15.0%, 41.9% and 17.2%; Nitrate nitrogen increased slightly. On the whole, the comprehensive emission reduction effect of Huoluobang Irrigation Area is obvious.

4.3 Analysis of power saving effect

According to the statistics on the use of irrigation power in recent four years in the Huoluobang Irrigation Area, the irrigation power consumption in 2014, 2015, 2016 and 2017 were 13949 kW • h, 19343 kW • h, 10644 kW • h and 15170 kW • h. See Table 4 for the power consumption of Huoluobang Irrigation Area in recent four years.

Table 4 Statistics of Electricity Consumption in Huoluobang Irrigation District from 2014 to 2017

Year	Power consumption（kW·h）	Average power consumption per mu（kW·h mu^{-1}）	Rainfall frequency (June to September)
2014	13949	25.4	10%
2015	19343	35.2	20%
2016	10644	19.4	65%
2017	15170	27.6	8%

According to the drainage frequency analysis of the rainfall during the 60 year rice irrigation period (June to September) in Pinghu City, the corresponding rainfall frequencies in 2014, 2015, 2016 and 2017 are 10% (once every 10 years), 20% (once every 5 years), 65% (once every 1.5 years) and 8% (once every 12.5 years) respectively. It can be seen from the vertical comparison that the electricity consumption in 2016 decreased by 24% compared with 2014 and 45% compared with 2015; In 2017, as there was basically no rainfall from the end of June to the beginning of August during the main water use period for rice, water and electricity consumption increased significantly, but also decreased by 22% compared with 2015. It can be seen that the Huoluobang Irrigation Area has achieved remarkable power saving effect through the upgrading and transformation of irrigation facilities and the later water management.

4.4 Analysis of yield increase effect

According to the analysis of rice growth data of test fields and nearby control fields in Huoluobang Irrigation Area, under water-saving irrigation, rice growth has not been significantly affected. See Table 5 for rice yield in different fields.

Table 5 Summary of Rice Yield in Experimental Fields

Index	Control				Experimental field			
	Control 1	Control 2	Control 3	Average	Exp.1	Exp.2	Exp.3	Average
Number of rice plants / N mu-1	107300	105850	108750	107300	107900	108300	108750	108317
Average plant height / cm	89.9	91.2	91.3	90.8	90.2	92.1	90.5	90.9
Average spike length / cm	14.6	15.5	15.9	15.3	15.4	14.7	15.8	15.3
Empty rate / %	9.0	10.0	11.0	8.4	7.6	8.3	9.2	8.1
1000 grain weight / g	23.3	22.9	23.1	23.1	23.3	22.3	23.1	22.9
Actual yield / kg mu^{-1}	552.3	553.6	551.5	552.5	557.8	559.0	562.4	564.2

Note: The average plant height and spike length are the average values of the representative 5 plants.

It can be seen from Table 5 that there is no significant difference in the number of plants, the rate of empty leaves, and the yield between the test plot and the control plot. It can be seen that under the condition of water-saving irrigation in Huoluobang Irrigation Area, the goal of not reducing rice yield can be guaranteed.

5. Conclusion

(1) The irrigation area has complete facilities, and the environment has been improved significantly. Through the construction of modern irrigation and drainage engineering system, the irrigation and drainage facilities in Huoluobang Irrigation District are completely new, realizing the full coverage of PE irrigation pipes, supporting the first field of metering facilities, real-time transmission of water quantity, frequency conversion control of water pumps, etc., which is in line with the development direction of modern irrigation areas. After reconstruction, the irrigation and drainage facilities in the irrigation area have been significantly improved, and the environmental outlook of the irrigation area has been significantly improved.

(2) The total water consumption is effectively controlled, and the effect of saving water and electricity is obvious. The Huoluobang Irrigation District has improved water efficiency (33% water saving in 2016 and 23% water saving in 2017) and saved electricity consumption (45% and 22% respectively in 2016 and 2017 compared with 2015) through metering facilities, dynamic monitoring of water volume, and total amount control and quota management, laying a foundation for scientific water use and efficient irrigation in the next step.

(3) Significant emission reduction of non-point source pollution and initial achievements in ecological defense line. The ecological ditches and hetang wetlands in irrigation areas can effectively intercept rainfall runoff and paddy field drainage, and use the physical, chemical and biological mechanisms in the wetland ecosystem to significantly reduce the concentration of nutrients in water (the permanganate index, total phosphorus and total nitrogen combined emission reductions of the three defense lines are 39.7%, 41.9% and 17.2% respectively), indicating that the three defense lines of fields, ecological ditches and hetang wetlands have achieved initial results, The aquatic plants in the three lines of defense have obvious absorption of nitrogen, phosphorus and other substances, reducing the emissions of non-point source pollution in farmland, and achieving the goal of water saving and emission reduction.

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STUDY ON DESIGN OF PADDY FIELD IRRIGATION SYSTEM BASED ON PREFABRICATED SHAFT PUMP STATION

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ABSTRACT

The prefabricated shaft pump station is a new type of intelligent, integrated and assembled irrigation and drainage pump station applicable to a variety of environments. It extracts River and lake water in the form of agricultural pumping wells, which changes the structural form of the traditional pump station consisting of water inlet tank, pump room and pump room. It has the advantages of low investment (saving 40% - 60% compared with traditional pump stations), short construction period (1-2 days for small-sized pump stations, 5-10 days for medium-sized pump stations, and 40-60 days for traditional pump stations), no occupation of arable land (the whole pump station is buried below the ground, does not occupy arable land, and does not affect agricultural machinery farming), no fear of siltation (the water inlet is provided with anti silting cover plate, and the river silt can be automatically lifted up and the water can be normally lifted) Convenient opening and closing (one key start, no vacuum pumping, no water filling), convenient management and maintenance. In this paper, a paddy field project area is taken as the research object, and the paddy field irrigation system is designed based on the assembled shaft pump station. The general layout of the system, determination of design flow, pipeline design, field engineering, pipeline hydraulic calculation, pump station selection, and key points of pump station design and installation are comprehensively introduced.

Keywords: Paddy field; Irrigation system; Prefabricated pump station; Design

1. Introduction

The pump station is a device that can provide hydraulic power and pneumatic power with a certain pressure and flow. The traditional pump station is mainly composed of intake chamber, grille chamber, forebay, pump room, management room, etc. It covers a large area, requires ground buildings, and has high civil construction costs. With the continuous improvement of equipment and the development of automatic control and remote monitoring, the emergence of integrated pump stations has been used to replace traditional pump stations in some occasions. Integrated pumping stations have been used in Europe for nearly 50 years, accounting for more than 70% of the total number of pumping stations. China introduced an integrated pump station in 2010. Due to its small floor area, fast construction speed, simple operation and maintenance, and small impact on the surrounding environment, although it is widely used in China, it is still used less in agricultural irrigation. In recent years, with the development of water-saving irrigation technology, the application of water transmission pipeline is becoming more and more popular, and the number of irrigation pump stations is increasing, while the traditional pump stations have the disadvantages of long construction period and occupying farmland, It restricts the application of water-saving irrigation technology.

2. Brief introduction of prefabricated shaft pump station

Assembled shaft pump station is an integrated pump station developed for agricultural irrigation based on the existing integrated pump station, integrating machinery, electronics, control, computer, information, communication and other technologies. The pump station is mainly composed of five parts, including the intake barrel, the pump room, the pump system, the hydraulic system, and the control system. The water pump room is equipped with trash rack, trash remover, anti silting gate, hydraulic lifting device, float level controller, hydraulic pipeline, gate positioning opening and closing controller, etc; The water pump system is equipped with submersible sewage pump (or submersible axial flow pump), water outlet pipeline, flowmeter, pressure sensor, check valve (flap valve), etc; The hydraulic system is equipped with hydraulic station, control valve, hydraulic oil cylinder, hydraulic oil pipe, etc; The control system is equipped with cabinet shell, power supply circuit breaker, hydraulic station, frequency converter (soft starter), electricity meter, PLC, LCD display, control panel, water pump

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protection module, current, voltage, flow and pressure display, manual control button, antenna, lightning protection and grounding, camera, etc.

The pump station is buried underground as a whole, which does not occupy farmland and affect agricultural machinery farming; There is no pump room, no exposed facilities, monitoring, and no need for care; Open the well cover to take out the water pump, which is very convenient for maintenance; The construction period of small pump stations is 1-2 days, and that of medium pump stations is 5-10 days. Compared with the traditional pump station, the pump station has the advantages of short construction period, no occupation of farmland, convenient management and maintenance, etc.

3. Overview of the Project Area

Water saving irrigation technology is vigorously promoted in the project area. At present, the main water-saving irrigation technology is canal seepage prevention, and the control irrigation technology of "thin, shallow, wet, sun" is promoted in the irrigation project. Water saving irrigation technologies such as land leveling, straw mulching, plastic film mulching, long border sectional irrigation, wide and shallow border and ditch combined irrigation, and horizontal border irrigation should be promoted in the field surface irrigation management. Some high-yield paddy field bases and economic fruit forests have developed efficient water-saving technologies such as low pressure pipeline irrigation, sprinkler irrigation, and drip irrigation. The irrigation area of the high-yield paddy field base in the project area is 1500 mu, the crops are rice, and the water intake point is the main canal of a reservoir.

4. Irrigation system engineering design

4.1 General layout

The project area is located in a high-yield paddy field base, and it is proposed to use low pressure water conveyance irrigation technology to replace the original channel irrigation. The irrigation system is mainly composed of water source, water transmission pipeline, water supply and distribution device, safety protection facilities and field irrigation facilities. The structure type of the pipeline system is a fully enclosed pipeline water conveyance irrigation system. The pipeline layout is parallel to the existing ditches, canals and roads. The buried main pipe, branch main pipe and branch pipe are used for three-stage fixed pipelines. The layout form is a dendritic layout. The spacing between branch pipes is 50~150 m, and the spacing between water supply devices is 40~80 m. The drainage and sand drainage facilities are set at the end of each branch pipe (the lowest point) according to the actual terrain.

4.2 Determination of design flow

According to the crop planting structure in the project area, using the water quota standard in this area, it is found that the water supplement quota for rice at 90% assurance rate is 400 $m^3mu^{-1}a^{-1}$. According to the analysis of local hydrological data, August has the largest water consumption, the irrigation quota is 200.1 m^3mu^{-1}, the irrigation period is 10d, and the maximum irrigation quota is 67 m^3mu^{-1}.

According to the Technical Code for Pipeline Irrigation Engineering (GB/T 20203-2017), the calculation formula for design flow of irrigation system is:

$$Q_0 = \sum_1^e \left(\frac{a_i m_i}{T_i}\right) \frac{A}{t\eta} \qquad (1)$$

Where Q_0 is design flow of irrigation system, a_i is the planting proportion of the ith crop during the peak irrigation period, m_i is irrigation quota of the ith crop during irrigation peak, T_i is duration of one irrigation for the ith crop during the peak irrigation period (10d), A is designed irrigation area (100 hectare), t is ystem daily working hours (16h), η is irrigation efficiency (0.86) , and e is types of crops irrigated at the same time during the peak period of irrigation. After calculation, Q_0=730m^3 h^{-1}.

4.3 Pipeline design

1. Design flow of pipes at all levels

$$Q = \frac{n}{N} Q_0 \qquad (2)$$

Where Q is design water delivery flow of a pipeline, n is number of hydrants opened simultaneously within the control range of the pipeline, N is number of hydrants opened simultaneously in the whole system (12), Q_0 is design flow of irrigation system (730 m^3 h^{-1}).

When 3 water hydrants are opened for each branch pipe, the flow classification is 61 m^3 h^{-1}, 122 m^3 h^{-1}, 183 m^3 h^{-1}, 366 m^3 h^{-1}, 549 m^3 h^{-1}, 730 m^3 h^{-1}.

2. Pipe diameter selection

According to the Technical Code for Pipeline Water Transmission Irrigation Engineering (GB/T 20203-2017), the pipe diameter is calculated according to the following formula:

$$D = \sqrt{\frac{4Q}{\pi V}} \tag{2}$$

Where D is pipe diameter, *Q* is design water delivery flow of pipeline (61~730 m^3 h^{-1}), *V* is design flow rate of pipeline, 1.5 m s^{-1}).

According to the calculation, the pipe diameters of pipes at all levels are 450 mm, 400 mm, 355 mm, 250 mm, 200 mm and 160 mm respectively.

3. Pipe material selection

By comparing the advantages and disadvantages of steel pipe, ductile iron pipe, PVC-U pipe and PE pipe, PE pipe is adopted for all pipes, and the maximum nominal pressure of the pipe is 0.6 MPa.

4.4 Field works

Field works mainly include water hydrant and field energy dissipation facilities. DN100 screw movable valve semi fixed water hydrant is used for water hydrant, and C25 concrete bottom plate is used for energy dissipation facilities×wide×High (350×350×400 mm) C25 reinforced concrete precast shaft and C25 precast concrete cover plate, and 150 mm water outlet is reserved in the shaft.

4.5 Hydraulic calculation of pipeline

The head loss shall be calculated according to the design flow of pipes at all levels and the pipe diameter preliminarily selected. The head loss along the pipeline is calculated according to the following formula:

$$h_f = f\frac{Q^m}{D^b}L \tag{3}$$

Where H_f is frictional head loss, L is pipe length, f is friction coefficient of pipe (0.948×10^5), m is flow index (1.77), b is pipe diameter index (4.77), D is inner diameter of pipe. According to the flow and length of pipes at all levels, hf=10.77mm

The local head loss coefficient of the pipeline is calculated according to the following formula：

$$h_j = \xi\frac{v^2}{2g} \tag{4}$$

Where h_j is local head loss of pipeline, ξ is local loss coefficient, *v* is flow rate in pipe, g is gravitational acceleration,. Through calculation, h_j=1.08m. The total head loss of the pipeline is 11.85m.

4.6 Pump station selection

The maximum and minimum working head of the system is calculated by the formula according to the Technical Code for Pipeline Irrigation Engineering (GB/T 20203-2017):

$$H_p = H_0 + Z_0 - Z_d + h_0 + \sum h_{f0} + \sum h_{j0} \tag{5}$$

Where H_p is the design head of the water pump of the irrigation system, H_0 is design working head of pipeline system (2m), Z_0 is pipe system inlet elevation (46.37m), Z_d is water level of pump station forebay or dynamic water level of pump shaft, (43.56m), h_0 is height difference between the center line of water supply device outlet and the ground at the reference point, the elevation of the outlet center line of the water supply device shall be the highest ground elevation in the field under its control plus 0.15 m, 0.8 m. $\sum h_{f0}$ and $\sum h_{j0}$ are respectively the head loss along the pipeline and the local head loss from the inlet of the pump suction pipe to the water supply device at the reference point (11.85m). After calculation, Hp=17.46m, the design lift of the water pump of the irrigation system is 17.46m.

According to the lift and flow, type I assembly shaft pump station is selected. The shaft diameter of this type of pump station is 1000m, and it is equipped with remote control system, remote monitoring system, flow metering system, image system and control cabinet room.

4.7 Key points of pump station design and installation

The flow and head of the assembled shaft pump station shall be determined in the design process, so as to select the pump and determine the pump station model; When selecting the site of the pump station, you can choose the riverway, ditch bank, riverbed and slope stability section. The pump body can be directly installed on the river and ditch slope. The installation elevation of the control cabinet must be higher than the maximum operating water level.

5. Conclusion

Assembled shaft pump station is a cross integration of machinery, electronics, control, computer, information, communication and other disciplines. Its development and progress depend on and promote the development and progress of related technologies. Looking at the development status and trend of the integration of various industries at home and abroad, the integrated control of small and medium-sized pump stations will develop towards modularization, networking, energy conservation, digitization, etc. Especially in the agricultural pipeline irrigation, the traditional pump station has the disadvantages of large investment, long construction period, occupation of farmers' farmland, high operation and maintenance costs, and there are big problems in project landing, implementation, and benign operation. The prefabricated shaft pump station can effectively solve the problems of traditional pump stations, and is more suitable for agricultural irrigation development.

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MANAGEMENT, OPERATION AND MAINTENANCE STATUS AND APPROACH: MOVE AHEAD FOR ENHANCING THE PERFORMANCE OF IRRIGATION SYSTEM IN NEPAL

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ABSTRACT

Irrigation is one of the key inputs to enhance agricultural production and ultimately contribute to poverty alleviation and food security. Though the Government of Nepal (GON) in the past attempted to enhance the performance of irrigation systems with a view to increase the water and crop productivity, the end result has not been satisfactory. In this context, this paper examines the reasons associated with the dismal performance irrigation systems in terms of their management, operation and maintenance (MOM) through an in-depth review of existing literature, a series of consultation with irrigation professionals, and field visits for verifications. The results show that in most of the irrigation systems the processes of MOM are not well structured, and the irrigation systems operate more or less on ad hoc basis. Most of the systems are not operating as per the design mode or are optimized to meet the societal requirement of equitable and reliable delivery of water to the farmer's field. The lack of proper planning and institutional capacity, standard procedures for designing and prioritizing the maintenance work, proper record of information including maintenance log book, technical audit of maintenance of irrigation infrastructure for undertaking MOM of existing irrigation systems are key aspects of poor performance of the irrigation systems in terms of water delivery, financial recovery, institutional performance and agricultural productivity. In this context, a set of guidelines have been developed for enhancing the MOM of the existing irrigation systems. The Department of Water Resources and Irrigation (DWRI) intends to institutionalize these guidelines to build its institutional capacity and the capacity of irrigation practitioners and professionals toward the socio-technical aspect of irrigation management. This requires restructuring and strengthening the irrigation offices of DWRI and establishing appropriate regulatory provisions for enforcing the provisions made by the guidelines.
Keywords: MOM, Irrigation System in Nepal, Irrigation Modernization

1.0 BACKGROUND

Nepal is a country where irrigation development is central to policies of food security and poverty alleviation. Irrigation takes place in a diverse range of agroecological zones using waters from both the surface and groundwater sources. Of the 3.56 million ha of agricultural land, about 2.53 million ha is irrigable, and about 1.5 million ha currently has access to irrigation.

About 51 percent of the existing surface irrigation systems belong to the category of farmer-managed irrigation systems (FMISs) which are self-governing. Rests of the systems belong to the category of agency-built, which are either managed jointly with the community or managed solely by the community. Nepal has long history of farmers managed irrigation system (FMIS) and the systematic irrigation management system has been initiated in 1928, and attempt has been done to cover about 1.5 million ha of potentially irrigable lands. The first irrigation infrastructure developed by Government is Chandra Nahar Irrigation System (CNIS) to irrigate fertile land of Saptari district and presently, many of these agency developed irrigation systems are being managed jointly by the government agencies and respective Water Users Association (WUAs), which are termed here as joint managed irrigation systems (JMISs). The areas under JMISs cover about 437,000 hectares, which account for about 29% of the present irrigated area. This paper focuses on these JMISs.

Though the Government of Nepal (GON) in the past attempted to enhance the performance of these JMISs with a view to increasing water and crop productivity, the end result has not been satisfactory. A survey conducted in the

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recent past in 21 irrigation systems covering a total area of about 268,000 ha suggested that their overall irrigation efficiency remained between 30 and 40 percent, and their agricultural productivity was below 50 percent of the potential regional average (DWRI, 2019). Even having it's long history of development, the expected performance of these systems have remained much below the level of national average. Several plans, programs, and policies have articulated a wide range of management principles for undertaking the MOM of the existing irrigation systems with the primary objective of enhancing agricultural production and productivity. Participatory irrigation management for enhancing the service delivery, decentralization through irrigation management transfer, and sustainable irrigation management through O&M cost recovery are some of the key policy principles. Despite articulating these policy principles, their implementation has remained very weak. Lacks of supporting legislation, and resources are some of the reasons. The survey further suggested that a lack of institutional capacity in managing these systems is the principal reason for their dismal performance. Which need be enhanced through the improved irrigation system management, operation, and maintenance.

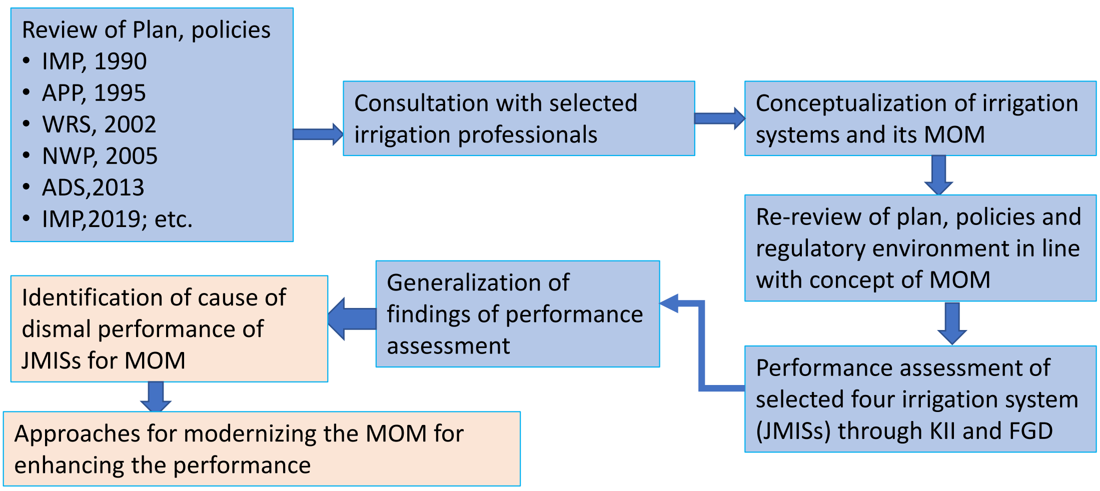
The situation depicted above necessitated the systemic procedures and guidelines to manage, operate and maintain the irrigation system. This can be achieved not only by engineering design, but also shaped by several other social and technical skill, and thus their management requires specialized knowledge. In this context, the objective of this paper is to conceptualize the irrigation system and its MOM (Management, Operation, and Maintenance) and finally present a plan for modernizing irrigation system in Nepal through the enhancement of their existing MOM practices.

2.0 MATERRIAL AND METHODS:

This paper is based on an in-depth review of existing literature, field visit, and series of consultation with irrigation professionals. The team of experts comprising water management expert, irrigation engineers, and institutional development expert reviewed the existing plan, guidelines, regulation, plan, and policies related to irrigation and water management and did first level of consultation with selected irrigational professionals to share the initial findings from literature review. Which helped to shape the objective of paper to prepare the basis of socio-technical guidelines on the MOM (Management Operation and Maintenance) and modernization of irrigation system. Those were mainly done with conceptualizing the irrigation system and its MOM.

With the defined concept of MOM, the existing plans, policies, and regulatory environments were reviewed in line with the concept of MOM. The gaps and how those contributing in the MOM status of existing JMIS were identified. After this, four JMIS were selected for the performance analysis to identify the reason of poor performance of the system, existing management plan, operation status, maintenance procedure, maintenance activities, existing institutional arrangement, existing cropping pattern,and crop productivity . Those were done mainly to know the performance of JMISs.

Key informant interview and focus group discussion at both field and departmental level were done to identify the cause pertaining to dismal performance of JMISs and approach to modernize them. The flow chart for overall methodological framework is in Figure 1.



* MOM: Management Operation and Maintenance; IMP: Irrigation Master Plan; WRS: Water Resources Strategy; NWP: National Water Plan; ADS: Agricultural Development Strategy;

Figure 1: Overall methodological framework

3.0 FINDINGS AND DISCUSSIONS

3.1 CONCEPTUALIZING IRRIGATION SYSTEM AND ITS MOM

3.1.1 Irrigation system

An irrigation system refers to both the physical infrastructure of works and the social infrastructure of rules and procedures which enable the acquisition, transportation, allocation, and delivery of water to farmers for irrigating their lands. An irrigation system primarily encompasses three subsystems namely the main system, distribution system, and water use systems.

The main system also termed here as the supply system, covers the headwork, main canal, and principal branch canals. It provides inputs to the distribution system, which covers all distribution canals up to the farm gates, and provides inputs to the water use system. The water use system covers areas under the farm gate/outlet which are solely managed by water users. As irrigation is input to agricultural production, not an end in itself, the water use system provides the actual outputs of an irrigation system. Figure 2 conceptualizes the input-output scenarios of an irrigation system

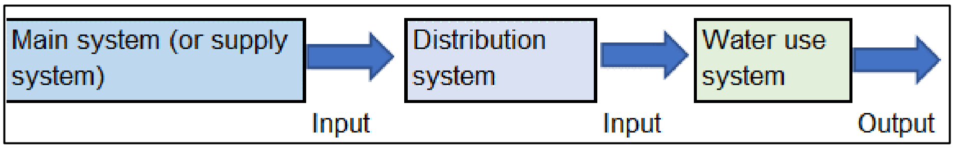


Figure 2: Input and output of an irrigation system

3.1.2 MOM of irrigation system

Broadly, the term MOM (management, operation, and maintenance) refers to the overall management of the irrigation systems for delivering irrigation water to farmers for enhancing agricultural production and water productivity. This is caused by the interaction between hydraulic parameters of infrastructure, institutional arrangements, and the people. It demands collective action by people (water users) and includes multiple tasks that relate to the management of infrastructure, water, organizational and institutional arrangements, resources, and agricultural systems. Figure 3 presents these tasks in pictorial form.

Figure 3: Component activities of MOM

In managing an irrigation system, all the above tasks need to be implemented in a coordinated approach. Thus, the arrangement for coordinated implementation of the above tasks is often described as the MOM of the irrigation system.

The paragraphs below describe these tasks and specify some of the tools for their operationalizatio

Management of water	Management of water comprises the three sub-activities namely water acquisition, allocation, and distribution. These sub-activities are operationalized through the canal operation plan (COP).
Management of infrastructure	Management of infrastructure refers to the timely and appropriate maintenance of the physical and electromechanical components of irrigation systems so that they last their economic life. This is achieved through the institutionalization of the asset management plan (AMP)
Organizational	Organizational management refers to setting up the organizational units (agency and

management	WUAs) and establishing institutional arrangements (rules in-uses) for collective actions
Resources management	Resources management refers to the assessment of the available resources, their collection, and utilization for managing the infrastructure and sustaining the organizations (agency and WUAs)
Management of agricultural production	Management of agricultural production refers to the integrated management of land, crop, and water through on-farm water management (OFWM) for maximizing agricultural production and water productivity. This aspect deals with the science of soil-water-plant relationships

3.2 MOM STATUS OF JMIS IN NEPAL

3.2.1 Plans, policies, and regulatory environments

History of irrigation management in Nepal date back to the Licchivi period. Since then, farmers throughout the country are managing several thousands of irrigation systems using their local ingenuity and skills.

The management of the agency-built modern irrigation system was first started during the Rana Regime in 1928 (1985 BS) with the construction of the Chandra Nahar (Canal). The Rana government then issued a regulatory document named then as “sanad ko sawal” that provided detailed directives for the management of the Chandra Nahar.

Though the management of agency-built irrigation systems was started in 1928, the thrust to irrigation development and management was accelerated only in 1987 with the introduction of the then basic needs program (BNP). Accordingly, for the first time, a working policy for irrigation development was issued in 1989. This policy initiated the concept of participatory irrigation management (PIM), which was later followed by Irrigation Management Transfer (IMT). Subsequently, the involvement of water users’ associations in all aspects of irrigation development and management was made mandatory through the irrigation regulation that was issued for the first time in 1989. This regulation was soon revised in 2000 after the issuance of the water resources act in 1992.

With the introduction of the Agricultural Perspective Plan in 1995, the 1989 working policy was revised as an irrigation policy in 1997, which was further revised in 2003 and 2013. Presently, the irrigation policy 2013 is in force. The table below presents the chronological events in the development of irrigation related perspective plans and their policy focus.

Year	Irrigation sector perspective plans	Initiated policy principles
1992	Irrigation Master Plan	Year-round irrigation
1995	Agriculture Perspective Plan (APP)	Irrigation management transfer, and On-farm water management (OFWM).
2002	Water Resources Strategy	Integrated Water Resources Management (IWRM) and river basin-based management of water resources
2005	National Water Plan	
2013	Agricultural Development Strategy (ADS)	Water Productivity
2019	Irrigation Master Plan	Year-round Irrigation

The above policies, plans, and strategies initiated a wide range of policy principles in the sector of irrigation management. Some such principles are

- Participatory irrigation management for enhancing the delivery of irrigation services through the formation and strengthening of WUAs
- Decentralization through irrigation management transfer
- Irrigation service fees for sustainable irrigation management.
- On Farm Water Management for enhancing irrigation efficiency and increasing agricultural production, and
- Inclusive irrigation management

Several plans, programs, and policies have articulated a wide range of management principles for undertaking the MOM of the existing irrigation systems with the primary objective of enhancing agricultural production and productivity. Participatory irrigation management for enhancing the service delivery, decentralization through irrigation management transfer, and sustainable irrigation management through O&M cost recovery are some of the key policy principles. Despite articulating these policy principles, their implementation has remained very weak. Lacks of supporting legislation, and resources are some of the reasons.

3.2.2 Performance of JMISs

Year-round irrigation, cropping intensity, irrigation efficiency, and rate of ISF collection are some of the most commonly adopted targets and indicators of irrigation performance. In addition, ADS 2013 also recognized water productivity as one of the performance indicators.

Literally, the term year-round irrigation resembles a situation in which farmers in an irrigation system have access to irrigation water all the time. However, such a situation is not possible under the prevailing upstream-controlled supplementary irrigation systems. As a result, year-round irrigation as an irrigation performance indicator is not being used that effectively, and this indicator is linked with cropping intensity

There exists a wide range of inconsistencies in the national-level targets of cropping intensity as set by periodic water plans. For example, Water Resources Strategy (WRS) in 2002 intends to achieve an irrigated cropping intensity of 250% by 2027, while the National Water Plan (2005) sets this target as 200% for the same planned period. Unlike this, the Irrigation Master Plan 2019 intends to achieve a cropping intensity of 205% by 2030. Similar is the situation for other indicators as well.

On the achievement side, existing data suggest that except in a couple of specific projects, there has not been much improvement in irrigated cropping intensity since early 2000.

The rate of ISF collection is highly discouraging. The departmental data suggest that the ISF collection as a percentage of O&M cost is only about 5.2% (DOI, 2020). This figure is based on the 5 years average of 24 JMISs, and the estimated average maintenance cost.

Data on operational indicators are not available. A recent study conducted in the Bagmati irrigation system suggests that the present water delivery service to individual fields is not close to the degree that would be required for modern farm irrigation methods. A specialized indicator that ranks the ability of the present water delivery service is 0.3 out of a possible 4.0 (ADB RDTA 2015).

3.2.3 Operation and maintenance of JMIS

After field visit and several consultations at field and departmental level, the status of operation and maintenance, performance of the system are not systematic, effective and sustainable. Except for a couple of JMISs where irrigation management transfer project (IMTP) was implemented in the recent past, most of the canals under jointly managed irrigation systems operate on an ad hoc basis. Their operational arrangements are agreed upon locally. Even in the previously implemented IMTP, the prepared canal operation plan, asset management plan etc. are not used effectively after project completion. The experiences of water guards and gate operators are the basis of flow regulation. The operation of these canals neither follows the designed mode of operation to meet the crop water demand nor do they operate to meet the societal requirements of equitable and reliable delivery of irrigation water.

Though time-series monitoring of flows in canals is the fundamental basis for their operation, most of the existing flow measuring devices (except the devices located at the intakes of some of the irrigation) are dysfunctional as they are not in use.

In irrigation systems where the command area is not developed, first-come-first-served is the basis of water distribution at their lower ends. Thus, farmers at the head ends of the canals tend to get more water. Further, in such systems, as the lower order canals (watercourses and field channels) are not yet well developed, lands that are adjacent to the minor canals get irrigation, while lands located at some distance from these canals do not have access to irrigation.

In such areas, either field-to-field irrigation is practiced (mainly for monsoon paddy), or temporary channels are built across neighbors' landholding for irrigating dry season crops downstream. The possibility of building a temporary channel across others' landholding is however shaped by the social cohesiveness of the farmers in the area. As land values have gone up tremendously due to rapid urbanization, such social cohesiveness hardly exists. As a result, lands downstream remain unirrigated.

Unlike the situation depicted above, in irrigation systems where command areas are developed and maintained, water distributions at lower ends are relatively better as the majority of landholdings already have access to watercourses or field channels.

The DWRI does not have standard procedures and practices in designing the maintenance of JMISs. As a result, maintenance works are identified on an ad hoc basis. Though maintenance needs are usually identified through a walkthrough of the concerned canal, a defined mechanism does not exist for prioritizing the maintenance needs based on the functionality and structural stability of the concerned structures.

Further, in most of the existing irrigation systems, besides undertaking the maintenance of existing infrastructure, the available maintenance budgets are being used also for the development of additional new infrastructure. As a result, the planning approach applied for the maintenance of existing infrastructure and the development of new ones remains the same. Further, there is no practice of maintaining the maintenance log of irrigation infrastructure. Also, the technical audit of maintenance of irrigation infrastructure has never been done.

The cost required for maintaining the irrigation systems seems to vary between 615 and 2,040 NPR/ha. Roughly, about 25% of the total O&M cost goes to operation. A substantial amount of operating costs is used in paying the work-charged staff deployed for the operation.

Despite the growth of JMISs both in terms of number and command area over the past several decades, the operation and maintenance (O&M) of these systems are yet to be made systematic, effective, and sustainable. A lot of efforts were made in the past to make O&M of JMISs effective and sustainable through Participatory Irrigation Management or Irrigation Management Transfer programs. Many of these irrigation systems were rehabilitated, WUAs were organized and instituted, and water users were trained with the objective that the concerned farmers would participate in the management of those irrigation systems with enhanced skills, and even completely take over the management of some of the systems. The results of those efforts are mixed. There has been some enhancement in the organizational, managerial, and technical skills of farmers, yet the upkeep of the irrigation systems and their operations are not satisfactory. Contrary to the expectation that some of the JMISs could be turned over to the respective WUAs for continuing their MOM, these systems still remain under JMISs, and their overall performance remain poor.

3.3 Causes Pertaining To Dismal Performance of Jmiss and Approach to Modernize Them

The forgoing sections noted that despite articulating several policy principles and attempts made in enhancing the performance of JMISs, the end results have not been that satisfactory. As a result, the agricultural productivity of most JMISs has remained nearly stagnant since the 2000s. The paragraphs below first describe the causes pertaining to the dismal performance of JMISs followed by suggested approaches to modernize them

3.3.1 Causes pertaining to the dismal performance of JMIS

Weak implementation of plans, programs, and policies as a result of a lack of regulatory systems for accountability aspects, deficiency in management principles, institutional incapability, and inappropriate development focus are some of the principal causes for the dismal performance of JMISs. These causes are summarized below:

Lack of regulatory system and accountability aspects*:* Lack of supporting regulations for defining the accountability aspects of key stakeholders in undertaking several tasks of irrigation management is one of the principal causes for the dismal performance of JMISs. For example, prevailing regulation is silent on maintenance arrangement, the basis for the fixation of irrigation service fees (ISF), procedures for billing and collection of ISF, public notice on irrigation scheduling and, legal actions to be taken against non-compliers of irrigation rules.

Though originally it was believed that participatory irrigation management could solve all kinds of managerial problems by building social consensus among the users, such a hypothesis no longer works due to rapidly changing socio-economic scenarios of the system areas. This situation thus demands an appropriate regulatory system.

However, while examining the policy and regulatory environment, it reveals that only the first two irrigation policies (1987 and 1997) and three periodic plans (BNP 1987, IMP 1992, and APP 1995) were supported by the irrigation regulations issued in 1989 and 2000. Though the irrigation policy was further revised in 2003 and 2013, these policies and periodic plans issued after 2000 were not supported by relevant regulations. As a result, even after 20 years of development, the irrigation regulation 2000 is still in force (Figure 4).

In the present scenario, as the country has already embarked on the federalism mode of governance with the three spheres of government, it is essential to establish an appropriate regulatory system to define the roles, responsibilities, and accountabilities of concerned stakeholders in undertaking several tasks of irrigation management.

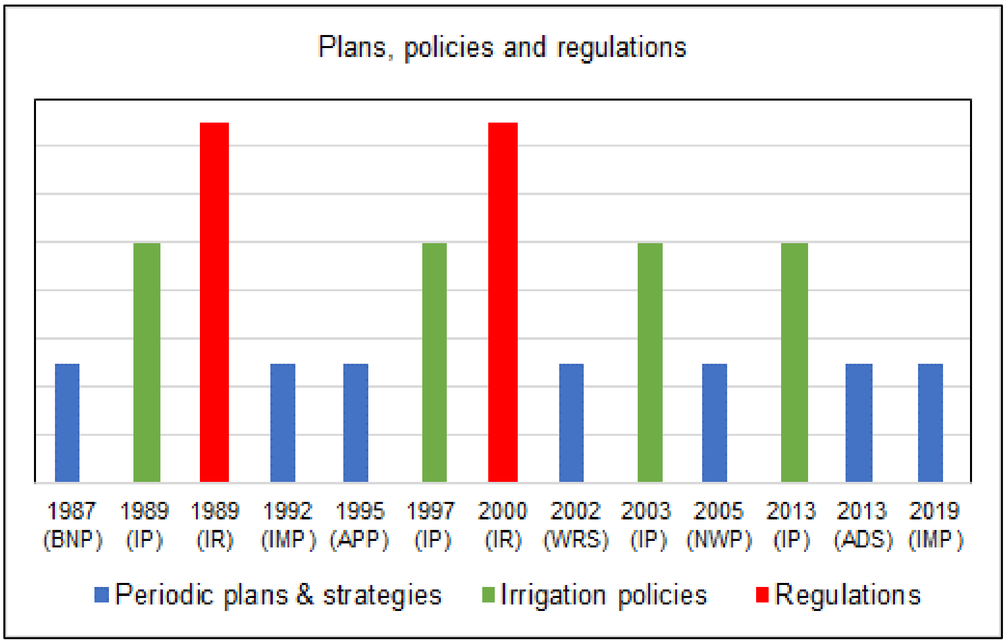


Figure 4: Plans, policy, and regulatory environments

Note: BNP (Basic Need Program), IP (Irrigation Policy), IR (Irrigation Regulation), IMP (Irrigation Master Plan), WRS (Water resources strategy), NWP (National Water Plan), and ADS (Agricultural Development Strategy)

Lack of management principles: Though the 2013 Irrigation Policy envisions enhancing agricultural productivity through sustainable year-round irrigation services, it lacks details on the management principles, working policies, and relevant tools for the reliable and equitable delivery of irrigation water, collection and management of ISF, and sustainable maintenance of irrigation systems. Thus, many JMIS, are suffering from a low level of productivity, low water use efficiency, negligible collection of ISF, poor maintenance, and ineffective WUA participation. As a result, the basic challenges to irrigation management in the past and the present have always remained the same - that is how to sustain the management, operation, and maintenance (MOM) of JMISs?

Lack of capacity (individual and institutional): Irrigation management involves a complex socio-technical phenomenon, and thus demands specialized knowledge requiring regular inter-disciplinary training. However, such a training program for irrigation professionals, WUAs, and farmers is non-existent though there are (were) a couple of project-based initiatives designed based on the tailored needs of the project. Further, there is a gap at the level of academic institutions as well. Although many engineering institutions recognize the gap between the knowledge required and the type of education they provide to students, their syllabus still focuses on conventional irrigation engineering, design and technical aspect of irrigation and drainage. In addition, there is no institutional mechanism by which the training needs on irrigation management could be addressed in a comprehensive manner by compiling the knowledge and skill that were gained in the past

Compared to the scope of the work at hand, the investment that the government has made in field-based studies (research) and capacity building in the irrigation management sector so far has remained inadequate. There is thus a need to take up an initiative in this sector, which needs to be widened to include people working with the provincial and local governments including INGOs, NGOs, consultants, and universities.

Inappropriate development objectives: The development objectives of most of the earlier irrigation management projects focused on enhancing the performance of JMISs through capacity building of the DOI and WUAs for delivering improved irrigation services to farmers (IWRMP-B, 2018). This is also revealed by the development objective of the recently completed IWRMP-B project, which stated:

To improve service performance and service delivery of selected public irrigation schemes (JMISs) in the terai through the completion and consolidation of management transfers to the WUAs (World Bank, 2018)

From the perspective of infrastructure development and irrigation management, most of the earlier irrigation management projects focused only on the main distribution system without considering the command area development at the level of the farm gate area that encompasses the development of field channels, related infrastructure, and OFWM. It was earlier believed that once the delivery of water to a group of farmers is enhanced, farmers would undertake the development of the command area within the watercourse and farm gate, and manage water therein on their own. This hypothesis no longer works. Even in an irrigation project in which the development of a farm gate command area was one of the principal components, it was difficult to develop field channels as planned. In this context, the staff appraisal report (Report No 6655-Nep) of the World Bank (World Bank, 1987) noted:

Stage 1 of the Sunsari Morang Irrigation Project (SMIP) covered an area of 9,750 ha. This system was designed and built up to a farm gate of 10 ha with a capacity to manage a designed flow of 66 lps (intermittent supply). To manage this flow within the farm gate, respective farmers were required to build field channels therein. But the World Bank (1987) noted that such field channels could be developed only in areas of about 2,000 ha.

The above situation raised concerns about whether the remaining 7,750 ha of the stage 1 area have access to irrigation water, especially during critical periods of irrigation.

The case of SMIP depicted above was reported in 1987 when the land value was much lower compared to the present-day land value, which has gone up sharply as a result of rapid urbanization. In this context, command area development within a farm gate should receive special attention irrespective of whether the responsibility of undertaking this task is entrusted to the irrigation agency, WUAs or farmers. Without appropriate command area development, access to irrigation water for each and every individual farmer within farmgate cannot be guaranteed for enhancing agricultural and productivity therein.

3.3.4 Recent development

To address some of the above issues causing dismal performance of JMISs, the Department of Water Resources and Irrigation (DWRI) in recent past undertook the following initiatives

- Recognizing the weakness of the 2013 irrigation policy in defining the principles of managing JMISs and under the changed political context of federal structure, a new irrigation policy 2022 (IP 2022) has been drafted through wider consultations at both the national and local levels. Presently, the Irrigation Policy 2022 is in the process of approval, which however is taking longer than required due to a lengthy bureaucratic process.
- In addition, recognizing that well-structured MOM guidelines are key to enhancing the MOM of JMISs, the DWRI under technical assistance from the World Bank, developed a set of MOM guidelines that includes seven independent guidelines for irrigation asset management, preparation of parcellary map, canal operation, calibration of hydraulic structures, resources management, WUA institutional development, and irrigation benchmarking. In addition, the MOM guidelines also recommend implementing a couple of strategic programs and innovative approaches for supporting the MOM enhancement process. This paper is the output of this work. These strategic programs mainly include command area development, on-farm water management, capacity building, and database management.

3.4 Approach to modernizing JMISs in Nepal

In the context noted above, the need of the day is to institutionalize the MOM guidelines within DWRI by operationalizing its provisions in modernizing a couple of JMISs through a MOM enhancement program (MOMEP). The paragraphs below first define irrigation modernization followed by conceptualizing the MOM enhancement program (MOMEP).

3.4.1 Irrigation modernization

Irrigation modernization is the process of upgrading or improving the irrigation system during which its original design and concepts are substantially modified for improving the delivery of irrigation services to farms or farmers. The said improvements in irrigation systems will be achieved by institutionalizing the provision of MOM through MOMEP.

3.4.2 Conceptualizing the MOM enhancement program

Considering that irrigation is input to agricultural production, not an end in itself, and the objective of MOM is to enhance agricultural production/productivity, the MOM enhancement program will cover the entire irrigation system consisting of the main system, distribution system, and water use system. It will have two main components namely modernization of the main and distribution system, and command area development. The table below summarizes these components.

Components	Detail activities and tasks
Modernization of the main and distribution systems	• Modernization of essential water control structure • Capacity building (institutional and individual) • Restructuring and strengthening WUAs • Institutionalization and internalization of MOM guidelines (mainly COP, AMP, and resources management) within DWRI
Command area development	• Development of field channels and related infrastructure at the farm gate and above (up to the level of the watercourse) • On-farm water management (OFWM) • Agriculture extension and market support • Integrated Crop and Water Management Program (ICWMP)

Figure 5 conceptualizes the MOM enhancement program (MOMEP) and likely institutional setup for its institutionalization within DWRI.

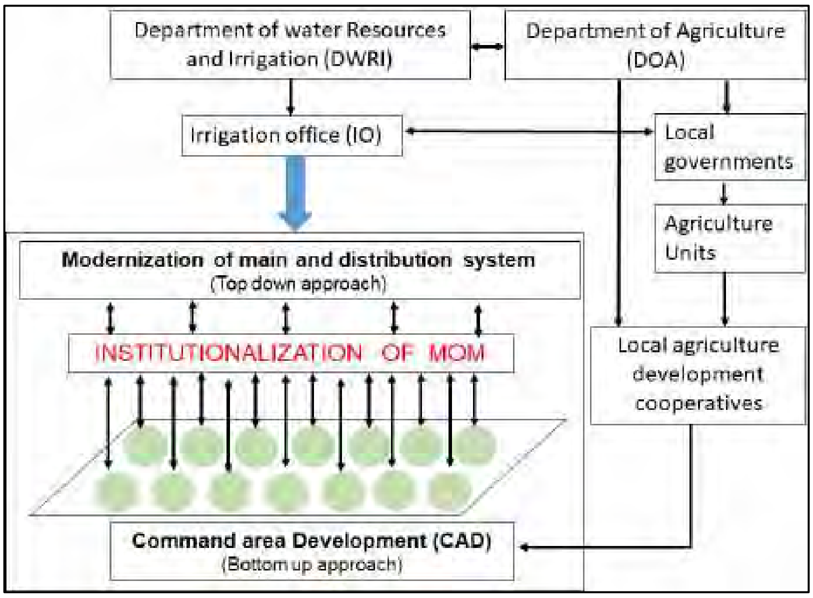


Figure 5: Institutional setup and institutionalization of MOMEP within DWRI

Modernization of the main system will start from the upper end of an irrigation system with a top-down approach, while the command area development will start from the farm gate (the lower end of an irrigation system) with a bottom-up approach. These two approaches (top-down and bottom-up) when integrated together will shape the overall MOM of an irrigation system, which ultimately help to enhance both agricultural productivity and water productivity.

Enhanced performance of JMISs, strengthened institutional capacity of DWRI and WUAs, and improved agricultural and water productivity will be the likely outcomes of the MOM enhancement program, while improved food security and livelihood of the local community will be the likely impact.

4.0 CONCLUSIONS

The paper suggests that the performance of JMISs in Nepal is not satisfactory mainly from the perspective of service delivery to irrigation users, agricultural productivity, and O&M cost recovery. Lack of regulatory system and accountability, lack of supporting legislation, absence of well-defined management principles, weak implementation arrangement, weak institutional capacity, and inappropriate development objectives are some of the principal causes.

Even after developing the irrigation infrastructure, DWRI focuses mainly on the engineering aspects and MOM still works on ad-hoc basis. Those necessitated the systematic procedure and guidelines to manage, operate, and maintain the irrigation systems, which can be achieved through the specialized knowledge (socio-technical approach). These could be the several guidelines of MOM.

Some such causes relating to the dismal performance of JMISs can however be addressed by operationalizing the set of MOM guidelines through a MOM enhancement program with two major components namely the modernization of the main and distribution systems following the top-down approach, and the farm gate command area development from the bottom-up approach. Operationalization of the MOM guidelines should however be supported by the appropriate regulatory systems for defining the roles, responsibilities, and accountability of key stakeholders, and addressing issues related to land management for command area development. In addition, operationalization of the MOM guidelines should also be supported by an appropriate capacity-building program and institutional restructuring of the DWRI. It should be internalized and institutionalized by DWRI to implement the above-mentioned guidelines, program, plan, and policies. In Nepal, development of major irrigation system almost in completion stage and now GoN has initiated management, operation, and maintenance of the irrigation system through systematic planning approach.

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CROP WATER USE AND WATER STRESS USING MULTI DATE RESOURCESAT SATELLITE DATA OF WESTERN UTTAR PRADESH

Paavan Kumar Reddy Gollapalli[1], Niharika Janga[2], B A Chivate[3]

ABSTRACT

Remote sensing-based approach was implemented for ETc estimation from Bagpath (Western Uttar Pradesh). To study this a NDVI rule-based classification was done for Kharif and Rabi Seasons by defining thresholds of different classes of the study area and it had an overall accuracy as 86.86% and 79.72% for Kharif and Rabi crops, respectively, with kappa coefficient as 0.81 and 0.712, respectively. Evaluation of NDVI profile clearly captures growing season of sugarcane–wheat and rice–wheat cropping system and enabled accurate mapping of crops in a study area. In Kharif and Rabi season the average value of PET in ranges between 4.41 to 5.91 mm/day and 3.30 to 5.42 mm/day respectively. In rice-wheat cropping system a peak was observed at September and February months with a Kcb value of 1.2 and 1.23 respectively. Kcb temporal profile in sugarcane-wheat cropping system also shows peak in September and February months with a value of 1.24 and 1.03 respectively but the here the peak value of wheat is low it may be due to mixed pixel combination with young sugarcane plantations. The ETc varied from 3.09 to 6.87 mm day−1 in June 2017 to April 2018 and the average value of ET for sugarcane is 4.29 mm day−1. Then annual water requirement of sugarcane for our study area is estimated as 2316.6 mm (for 18 months) and 1544.4 mm (for 12 months). The WS_LSWI from June 2017 to January 2018, In June stress was observed with value 0.56 but in September, October it is in decreasing order because of increasing vegetative growth of sugarcane and rice then again in November slightly it was increased and in December value reaches 0.50 because harvesting of rice and old sugarcane plantations. Water scaler values take a dip after December signifying about less water stress as wheat crop growth takes place in January, February and March and again in April higher stress was observed with a value of 0.69 because of harvesting of wheat taken place.

Keywords : Evapotranspiration, Water Stress, Basal Crop Coefficient, Land Surface Wetness Index

INTRODUCTION

Agriculture is the major sector of all economic sectors which has relevance by water scarcity. Currently agriculture accounts 70% of global freshwater withdrawals. Water is a crucial component for food production. The water resources in India are estimated at 4000 cubic kilometer given the geographical area of 3.3 million square kilometer and an average annual rainfall of 1170 mm. Nearly 50 per cent of this water is lost to evaporation, percolation, subsurface flows to oceans and only 1953 Billion Cubic Meter (BCM) of water is available. The temporal and special variation in the availability of water reduces it further to 1086 BCM (Phansalker and Verma, 2005).

Availability of less water causes physical limitation in plants. Movement of water, oxygen and carbon dioxide in and out of plant is governed by Stomata. During water stress, stomata close to conserve water which result into closing the pathway for the exchange of oxygen, water and carbon dioxide which result into decrease of photosynthesis (Porporato et al., 2001).

Hence, growth of leaves is affected by water stress more than root growth because roots can compensate more for moisture stress. Water stress causes reduction in photosynthesis which ultimately leads to reduction in growth and development crop. Factors influencing crop water stress include soil moisture, canopy temperature/evapotranspiration (ET), leaf water content and leaf water potential (LWP). Detection of water stress can help farmers in taking proper measure for reducing negative impacts on productivity. Water stress can be detected using Ground based techniques and remote sensing based techniques. In this paper, both methods are discussed and remote sensing based techniques are used for estimation of crop water use and stress.

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METHODS

2.1 Study Area

Study area comprises of Bagpath (Western Uttarpradesh). Western U.P contributes to 34 percent of total food grain production at state level and 6 percent at national level. Sugarcane is the dominant crop of this region.

2.2 Location

The study area is located between 28.8 deg and 29 deg latitude and 77 deg and 77.5 deg longitude. The western area is separated by river Yamuna which separates it from Haryana and Delhi. The study was conducted in Bagpath district of western UP. Figure.1 shows location map of the study area.

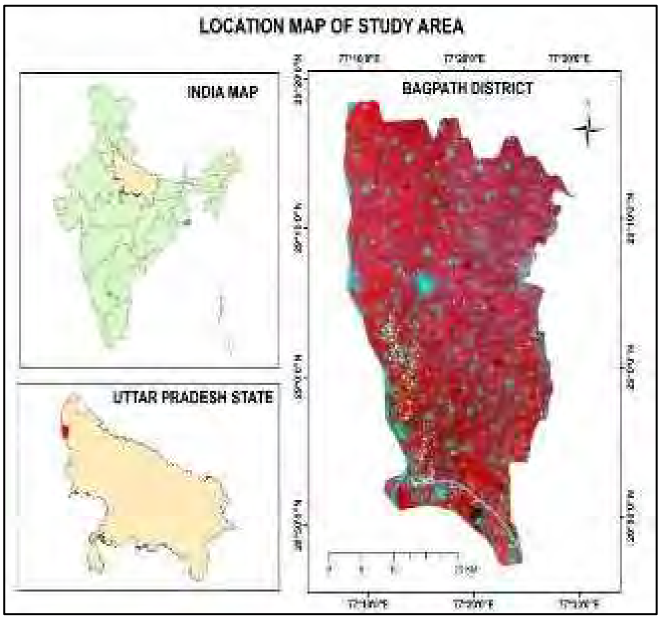


Figure 1: Location Map of the study area

2.3 Soils

Soil of Western UP is alluvium, coarse to medium in texture and moderately alkaline. They appear dark grey which indicate high organic matter composition. Region is spread with loam and silty to silty clay loam in most part of the region. (Nitika et al., 2016)

2.4 Farming system

Crop production is the major enterprise of farming community. Dairying forms another farming enterprise in this region. Agro-horticulture and agro-forestry are also emerging enterprises of farming system in this region. Sugarcane is the pre dominant commercial crop cultivation of this region. Field preparation for wheat cultivation generally starts in the month of November and continues till second fortnight of December because of delayed harvesting of sugarcane. More than 90% of area is covered with irrigated wheat with average of 4 to 5 irrigation is provided to the crop. (Nitika et al., 2016)

METHODOLOGY:

Crop evapotranspiration ETc is the basic information for the evaluation of crop water requirements and irrigation management. In this paper, ETc is estimated with Satellite derived ETo and Kcb approach. After the pre-processing of satellite images, ETc was estimated for the entire study area. The FAO-56 method is the most widely used method to compute ETo which is downloaded from MOSDAC website on daily basis. The basal crop coefficient Kcb is estimated using NDVI relation with Kcb. The Methodology adopted for this study can be understood by the following flowchart in figure.2

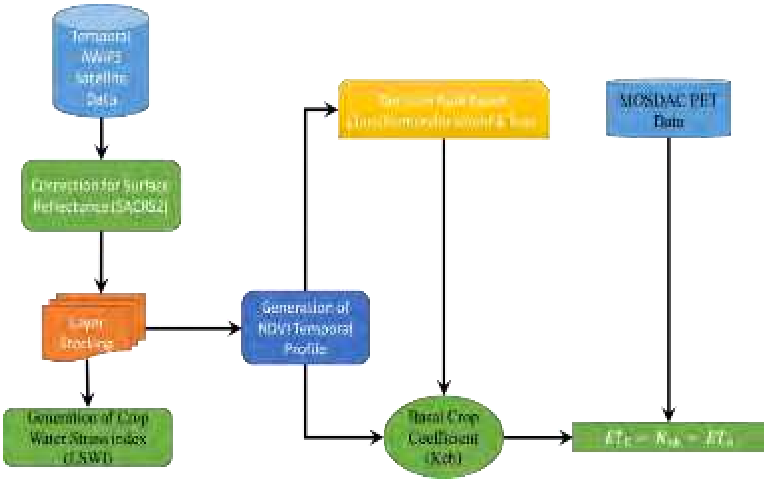


Figure 2 Methodology flowchart

3.1.1 Data Used

Satellite dataset used for this study are given in following table1. Sentinel data was used in February, March and April 2018 months due to non-availability of AWIFS data.

Table 1: Details of satellite data products used in this Study

S. No	Data Type	Date of Acquisition	Resolution
1	Sentinel-2A	25th April 2018 26th March 2018 14th February2018	10 m (Resampled to 56 m)
2	AWiFS	4thJune 2017 27th September 2017 17th October 2017 20th November 2017 18th December 2017 30th January 2018	56 m
3	INSAT-3D (PET_Daily)	8th April 2017 11th May 2017 4th June 2017 27th September 2017 17th October 2017 20th November 2017 18th December 2017 30th January 2018	5 km (Resampled to 56 m)
4	MOD04, 05, 08 Products	For Aerosal Optical Depth, Water Vapour and Ozone	Source Giovanni(Average value data)

3.2 Ground Measurements

GPS coordinates were collected from local sugar mill authorities for the sample sites for accurate identification of particular locations and for further analysis. Ground measurement site map is shown in figure 2. The ground truth points 12149 numbers of sugarcane and 3 numbers of wheat also collected.

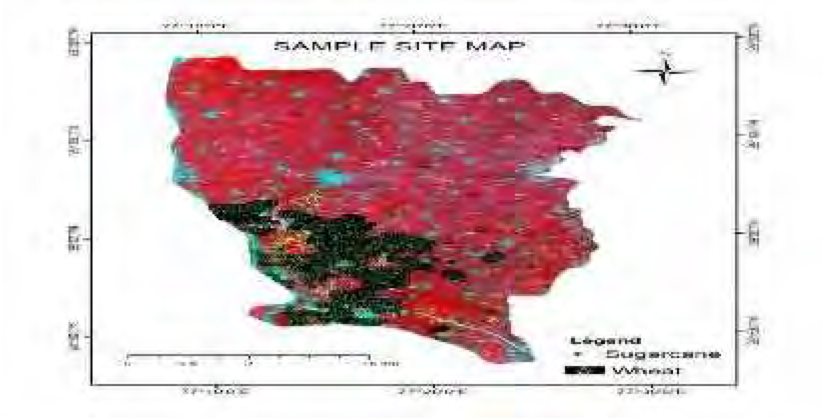


Figure 2: Ground measurement site map

3.3 Pre-Processing Of Satellite Data

Satellite data need to be converted to reflectance values from raw digital numbers and also needs haze removal if haze exists, for better visuality of the image. The package named SACRS2 has been developed using a C-program written for atmospheric correction of the RS2 AWiFS data. The code uses a method developed by Pandya et al. (2013) to correct the remote sensing signal perturbed due to molecular and aerosol scattering. Before correcting for atmospheric effects user needs to prepare a binary file having stack of the digital number data. The output files will be binary files in 4 byte floating point format. The output files do not contain map/projection information.

3.4 Crop Discrimination

Rule based classification technique was adopted using high to low resolution data i.e. AWiFS. Accuracy assessment of classified map was also done using independent reference sites of study area. Overall accuracy was defined as percentage of total independent referenced pixels that were correctly classified by rule based classifier. Producer's accuracy was also calculated by dividing the number of pixels correctly classified for each crop by the total number of independent referenced pixels for that crop. While the user accuracy is the fraction of number of classified pixels with respect to total number of classified pixels for the crop. Kappa coefficient was also calculated to measure the importance of classification result relative to chance agreement. A kappa value of one indicates perfect agreement between training pixels and their prescribed classes (Lillesand *et al*., 2004) and kappa value of zero indicate bad classification.

3.5 Basal Crop Coefficient

Crop coefficient Kcb is estimated from the equation 1 from observations of the normalized difference vegetation index (NDVI).

$$K_{cb} = K_{cb\,max} \frac{(NDVI - NDVI_{min})}{(NDVI_{max} - NDVI_{min})} \qquad (1)$$

Where $K_{cb\,max}$ is Basal crop coefficient and $K_{cb\,max}$ is Basal crop coefficient at effective full ground cover i.e., 1.3 (Hunsaker, 1994)

3.6 Potential Evapotranspiration

The potential ET rate (ETo) is influenced by several factors such as solar radiation, wind speed, air temperature and vapour pressure deficit. Among them, solar radiation is the most sensitive parameter influencing almost 60-70% variability of ETo . The potential evapo-transpiration (PET), hereafter referred as grass reference evapo-transpiration (ETo), is expressed in terms of amount of water transferred per unit time to atmosphere from water non-limiting surface covered with a uniformly and actively growing short grass such as Alfalfa. ETo represents the evaporative demand of the atmosphere for a given climatic region. Deficiency in required supply of moisture leads to water stress. The combination of spatial rainfall with ETo would help in monitoring water deficit and surplus during a growing season for rainfed agriculture. The accuracy of the PET product is about 80-90% (INSAT-3D Manual, 2015).

3.7 Crop Evapotranspiration

Crop evapotranspiration (ETc) refers to evapotranspiration of a disease-free crop, grown in very large fields, not short of water and fertilizer (Doorenbos and Pruitt, 1977). Estimation of ETc is essential for computing the soil water balance and irrigation scheduling. ETc is governed by weather and crop condition. Mathematically, ETc can be expressed as shown in the equation 2

$$ET_C = K_C * ET_O \qquad (2)$$

Where Kc is the crop coefficient which varies for different crops and their growth stages and ETo is the reference crop evapotranspiration.

3.8 Land Surface Wetness Index (Lswi)

LSWI uses NIR and SWIR regions of electromagnetic spectrum for stress assessment. This index is sensitive for the total amount of vegetation liquid and also for soil background. So, LSWI was estimated by following equation:

$$LSWI = \frac{NIR-SWIR}{NIR+SWIR} \qquad (3)$$

Estimated LSWI was further used in deriving water stress scalar (Ws) (Xiao et al., 2005).

$$W_S = \frac{1-LSWI}{1+LSWI_{max}} \qquad (4)$$

Where, LSWI is value of particular pixel and LSWImax is maximum LSWI value of particular pixel for a growing season

4. RESULTS AND DISCUSSION

4.1 Crop Discrimination

Temporal NDVI obtained from AWiFS was used for crop discrimination where separate rules were formed based on NDVI values of different seasons kharif (September) different classes were assigned. The NDVI values has been linearized between 0-255 by using the transformation NDVI*127.5+127.5 (Ray S S et al., 2000). Figure 3 & 4 shows crop inventory map of Kharif and Rabi seasons respectively and Table 2 & 3 shows accuracy assessment matrix for Karif and Rabi seasons respectively.

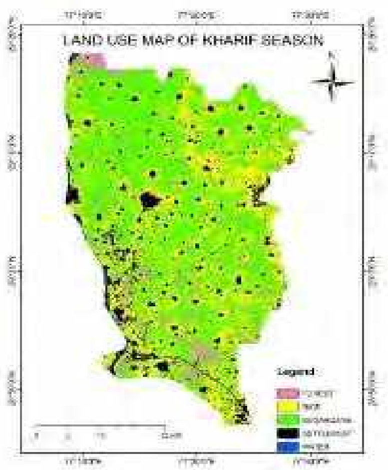


Figure 3: Shows the crop inventory map of Kharif Season

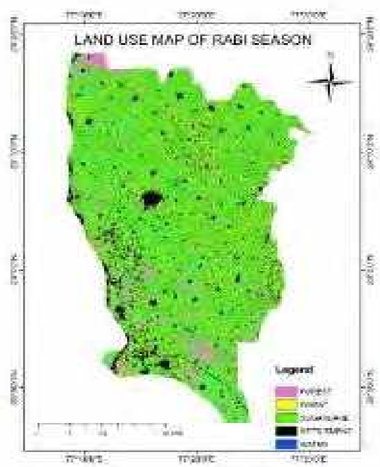


Figure 4: Shows the crop inventory map of Rabi Season

Table 2: The accuracy assessment matrix for Kharif

Classes	Refer. Total	Classified total	Correctly classified	Producer's accuracy	User's accuracy
Forest	454	499	421	92.73	84.37
Rice	714	742	613	85.85	82.61
Settlement	2327	2135	2007	86.25	94
Sugarcane	1332	1236	1196	89.79	96.76
Water	393	608	297	75.57	48.85
Overall Accuracy			86.86%		
Kappa Coefficient			0.8177		

Table 3: The accuracy assessment matrix for Rabi

Classes	Refer. Total	Classified total	Correctly classified	Producer's accuracy	User's accuracy
Wheat	1589	1151	739	46.51	64.21
Settlement	3338	3285	3009	90.14	91.6
Sugarcane	3845	3790	3372	87.7	88.97
Water Body	410	211	183	44.63	86.73
Forest	668	1413	549	82.19	38.85
Overall Accuracy			79.72%		
Kappa Coefficient			0.7132		

4.2 Ndvi Variation Throughout The Crop Season

Time-series of NDVI was generated from all 9 dates of AWiFS during crop growing seasons. The temporal and spatial variation in NDVI in the study area is represented in Figure 5 and 6 for Kharif and Rabi season of 2017–2018. NDVI with a maximum value in November, whereas during Rabi season (November to April) with a maximum value in February. The maximum value of NDVI denotes the peak growth stage of crops in Kharif and Rabi season, respectively. Higher average NDVI was observed in Kharif season as compare to Rabi season, this might be due to factors facilitating the faster crop growth in Kharif season: (i) higher moisture availability through rainfall (south-west monsoon); (ii) more photosynthesis in terms of higher sunshine hours; (iii) larger crop area occupied in Kharif season.

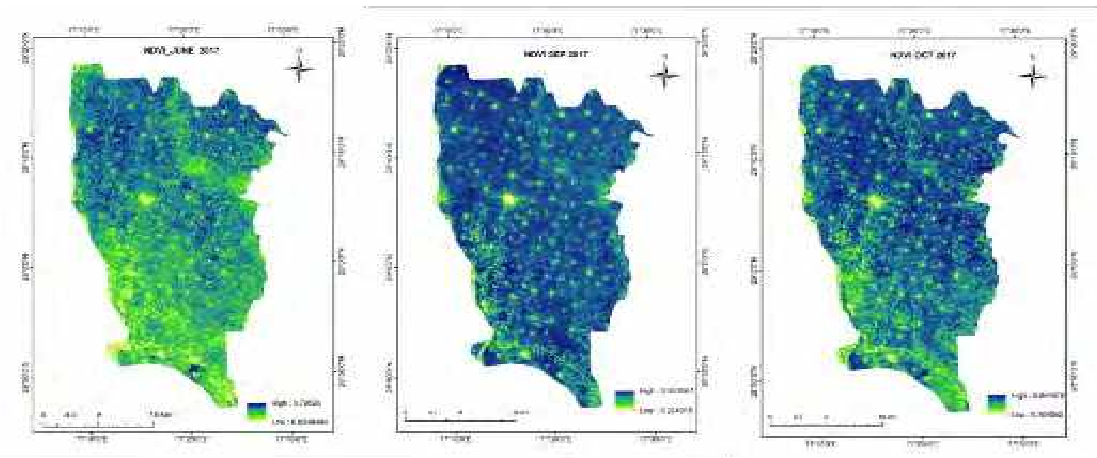


Figure 5: Spatial distribution of NDVI for June 2017 to April 2018

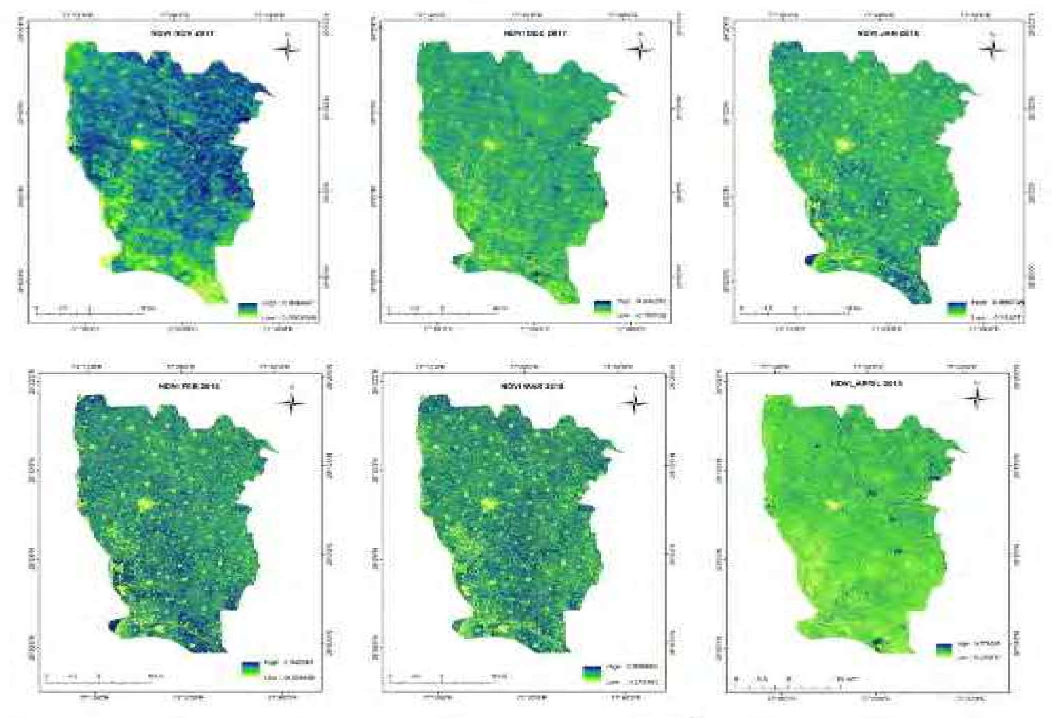


Figure 6: Spatial distribution of NDVI for June 2017 to April 2018

NDVI varied with crop and its phenological development throughout the season. Temporal variation in NDVI for sugarcane- wheat cropping system and rice–wheat cropping system are illustrated in Figure 7 and 8, respectively. It is evident that a dip in NDVI values was observed at December, 2017 in Figure 7 which defines the underneath growth of wheat in winter month after the harvesting of sugarcane and a young vegetative stage of sugarcane also. Most of the sugarcane had been harvested in December in sugarcane–wheat system. Moreover, a defined NDVI curve was observed for rice–wheat cropping system (Figure 8) which clearly shows the NDVI trend with continuous crop phenological growth for rice and wheat crops. These key points have differentiated these two systems very well. NDVI patterns represented here are similar to the NDVI patterns found by Kumari et al. (2013) in sugarcane–wheat and rice–wheat cropping system.

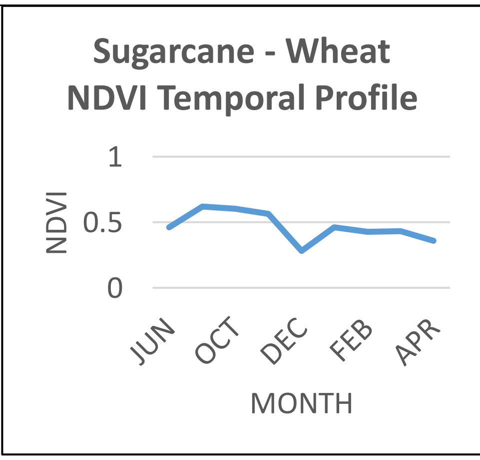


Figure 7: Temporal variation in NDVI for sugarcane–wheat cropping system

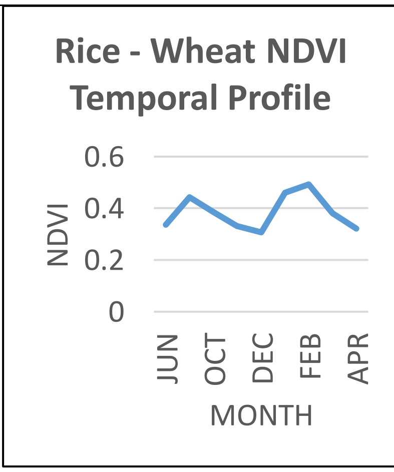


Figure 8: Temporal variation in NDVI for rice–wheat cropping system

4.3 Basal Crop Coefficient

The basal crop coefficient Kcb varied with crop and its phenological development throughout the season and ETc is also mainly depends on it, if it changes then crop water requirement also changes. The temporal variation of the Kcb in Rice-Wheat cropping system and Sugarcane-Wheat cropping system are illustrated in Fig. 9 A dip was observed in November and December, 2017 in Fig.10 and 11 because rice has harvested which was sown in Kharif season and again dip starts rising due to transplantation of wheat crop in Rabi season. Same profile has been evolved in Rabi season. Where ever it shows the peak in temporal profile, it represents crop is at highest vegetation growth and thus water requirement also will be more. In rice-wheat cropping system a peak was observed at September and February months with a Kcb value of 1.2 and 1.23 respectively. Kcb temporal profile in sugarcane-wheat cropping system also shows peak in September and February months with a value of 1.24 and 1.03 respectively but the here the peak value of wheat is low it may be due to mixed pixel combination with young sugarcane plantations.

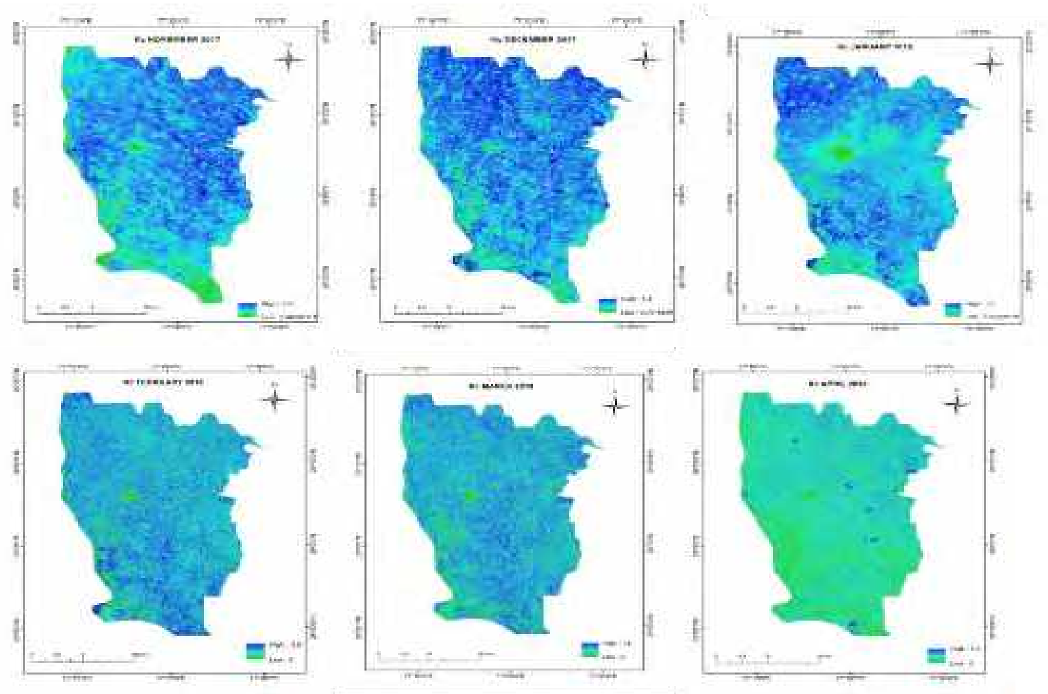


Figure 9: Spatial distribution of Kcb for June 2017 to April 2018

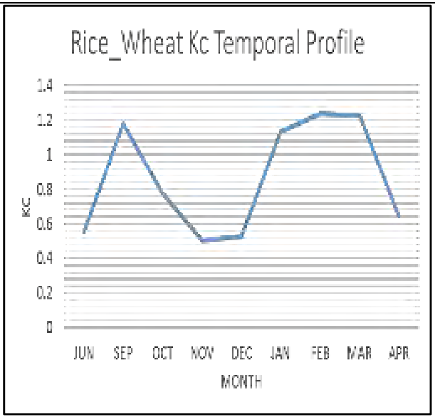


Figure 10: Temporal variation in Kcb for rice–wheat cropping

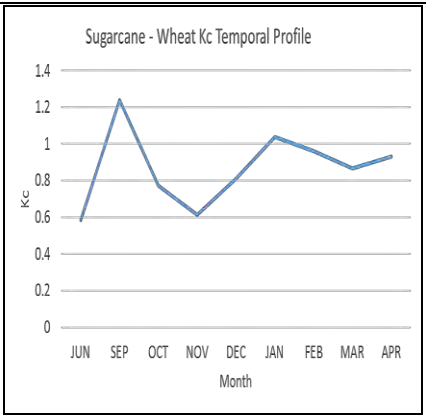


Figure 11: Temporal variation in Kcb for sugarcane–wheat cropping system

4.4 Potential Evapotranspiration

The daily PET data downloaded from MOSDAC with a resolution of 5 km is resampled to 56 m resolution of AWiFS data. This is an daily average data product and the units of the PET data is in mm/day. The accuracy of the PET product is about 80-90% (INSAT-3D Manual, 2015). The temporal variation of daily PET as shown in figure 12 and 13. In Kharif and Rabi season the average value of PET in ranges between 4.41 to 5.91 mm/day and 3.30 to 5.42 mm/day respectively.

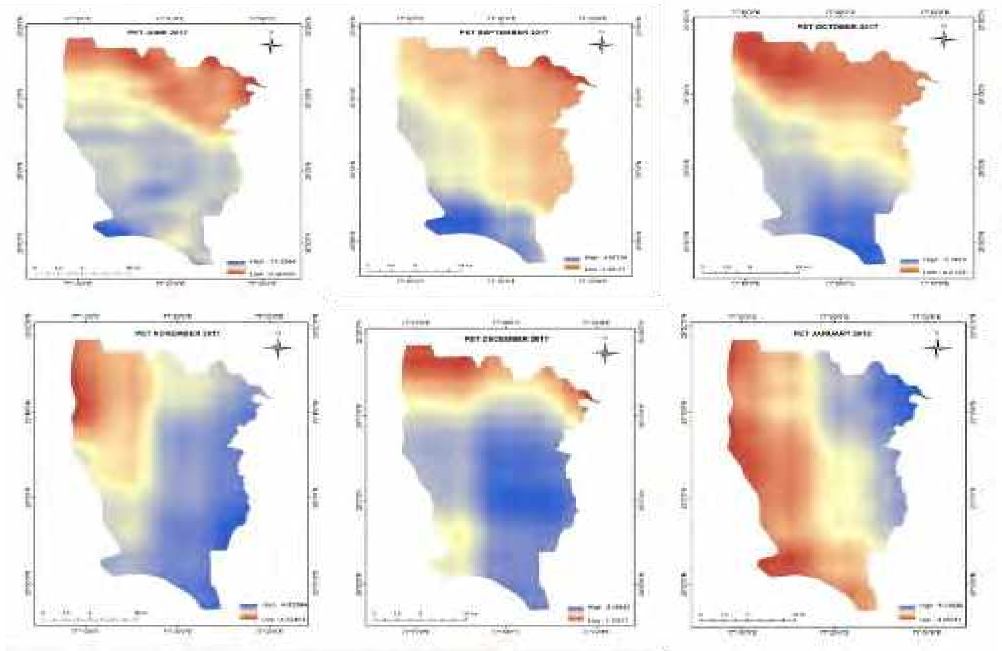


Figure 12: Spatial distribution of PET (mm/day) for June 2017 to January 2018

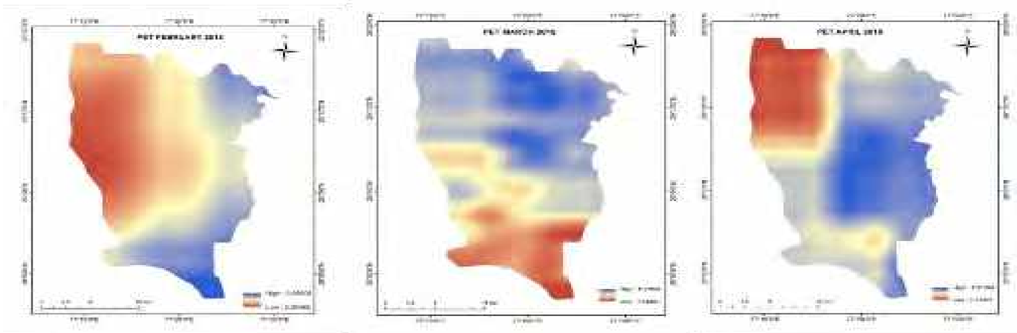


Figure 13: Spatial distribution of PET (mm/day) for February 2018 to April 2018

4.5 Crop Evapotranspiration

The PET daily data has been multiplied by basal crop coefficient (Kcb). The retrieved results of actual ET from basal crop coefficient and PET shows slight high values of ET can be observed in November but which decreases in February month this is because of sugarcane growth in November and by December most of it get harvested. So due to early vegetative growth of wheat in February lower values is being observed. The overall monthly images show a proper trend in spatial distribution of ET monthly wise.

Here, ETc varied from 3.09 to 6.87 mm day−1 in June 2017 to April 2018 and the average value of ET for sugarcane is 4.29 mm day−1. Sugarcane, an important cash crop of the country, requires considerable quantity of water during its entire crop cycle of 12-18 months, depending upon agro-climatic regions varying from sub tropical to tropical. The annual water requirement of this crop in sub tropical states like Uttar Pradesh, Punjab, Haryana and Bihar is 2000 mm (Shukla, S.K, 2017) and according to FAO it will be in range between 1500-2500 mm. Then annual water requirement of sugarcane for our study area is estimated as 2316.6 mm (for 18 months) and 1544.4 mm (for 12 months). The spatial distribution of ET and temporal variation has is shown in the following figure.

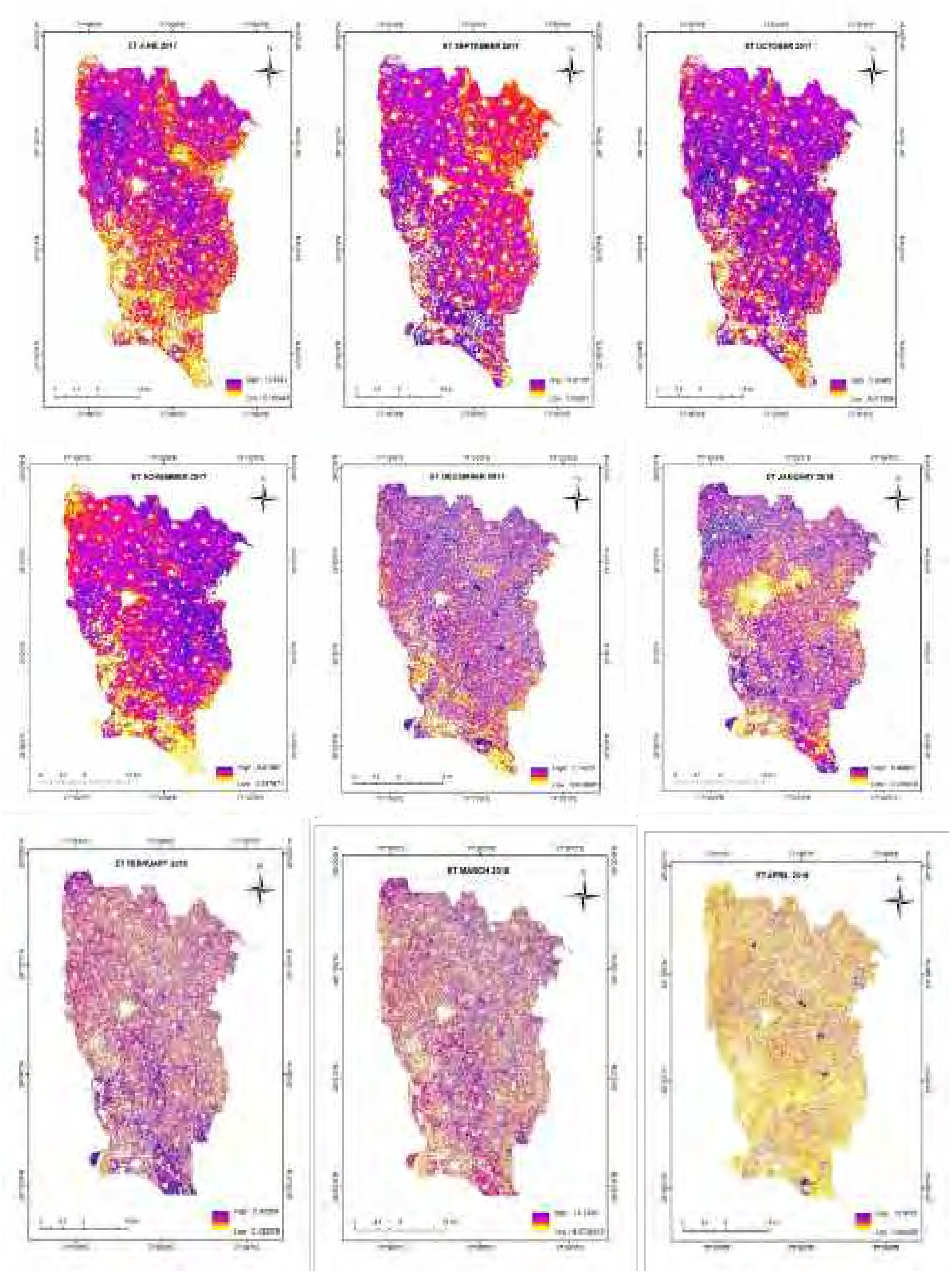


Figure 14: Spatial distribution of Daily ET (mm/day) for June 2017 to April 2018

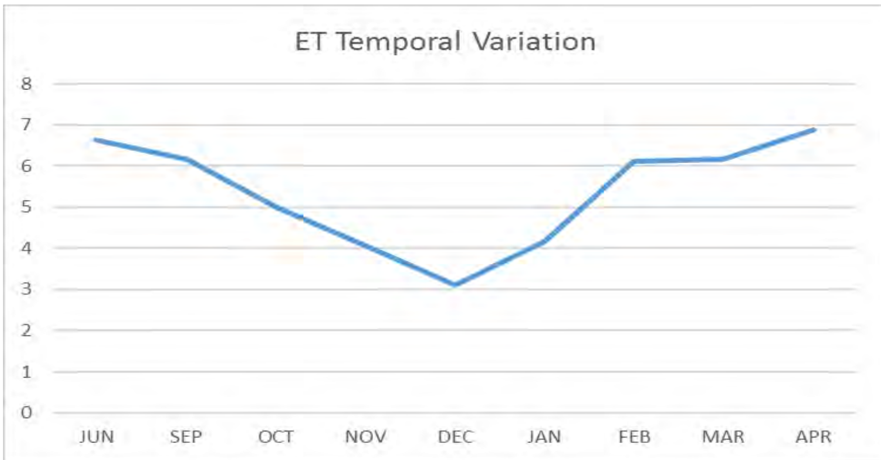


Figure 15: Temporal variation in ET

4.6 Land Surface Wetness Index (LSWI)

Land surface wetness index is a linear combination of NIR and SWIR bands. LSWI value ranges between -1 to +1 (Xiao et al., 2005).

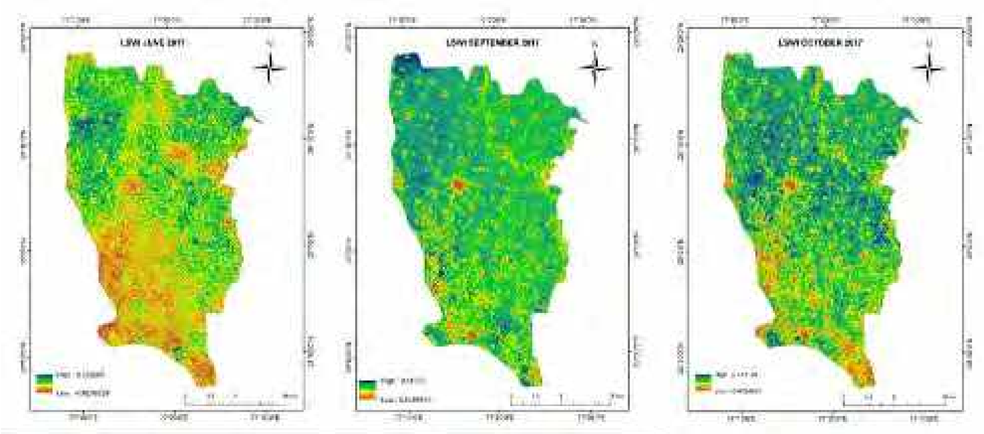


Figure 16: Spatial distribution of LSWI for June 2017 to October 2017

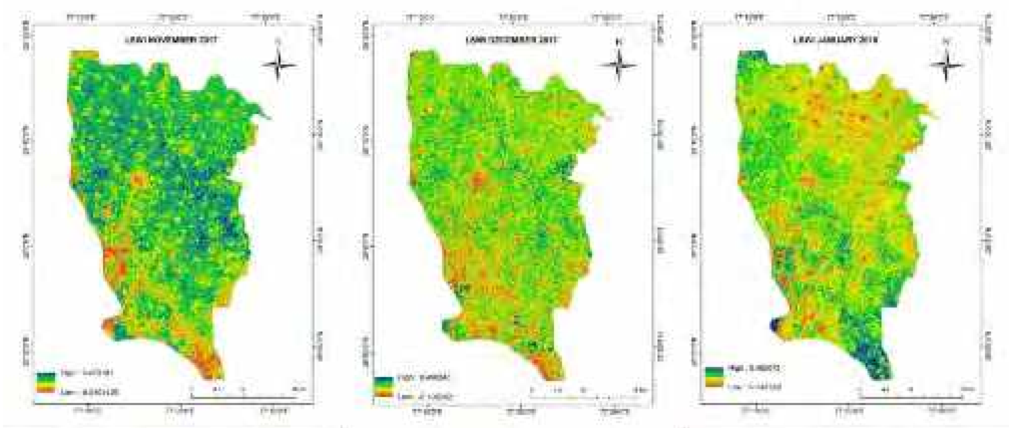


Figure 17: Spatial distribution of LSWI for November 2017 to April 2018

4.7 Water Scalar Land Surface Wetness Index (Ws_LSWI)

This index has a value range between 0 to 1, Where 0 signifies no stress and 1 signifies severe stress. Overall temporal distribution of water scalar can be observed in figure 18. As per the results obtained from June 2017 to January 2018, This is because of kharif crops followed by rabi crops continuously, hence it is under more stress and then February onwards harvesting of crops was started hence it is showing the minimum values from February to April. In June stress was observed with value 0.56 but in September, October it is in decreasing order because of increasing vegetative growth of sugarcane and rice then again in November slightly it was increased and in December value reaches 0.50 because harvesting of rice and old sugarcane plantations. Water scaler values take a dip after December signifying about less water stress as wheat crop growth takes place in January, February and March and again in April higher stress was observed with a value of 0.69 because of harvesting of wheat taken place.

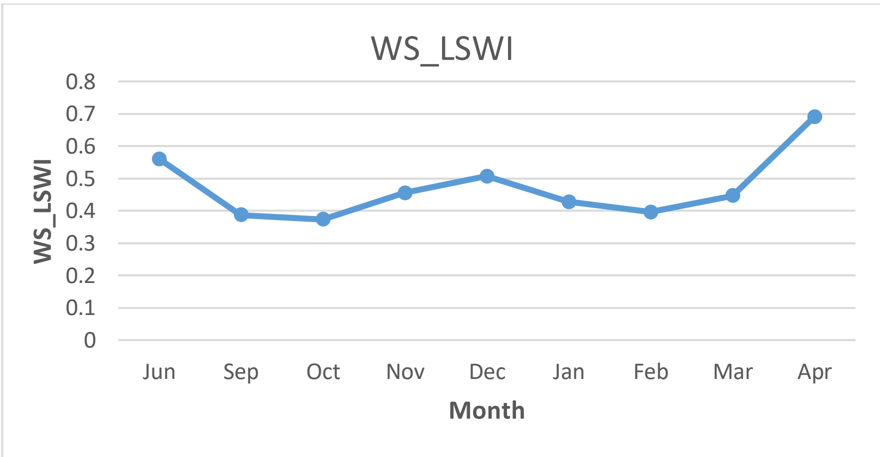
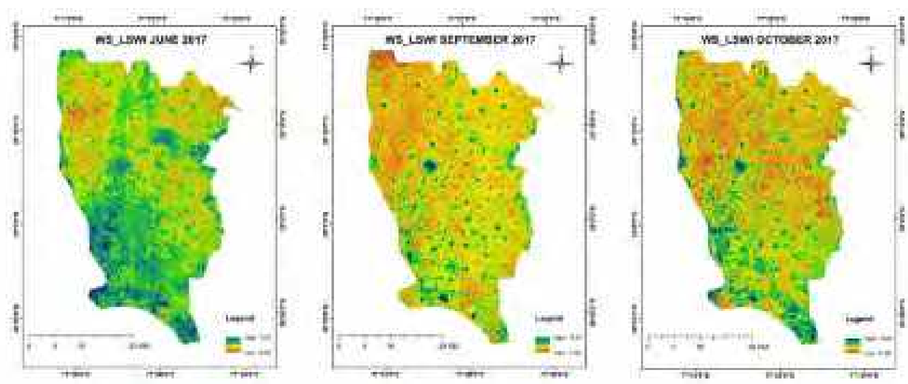


Figure 18: Temporal variation in WS_LSWI



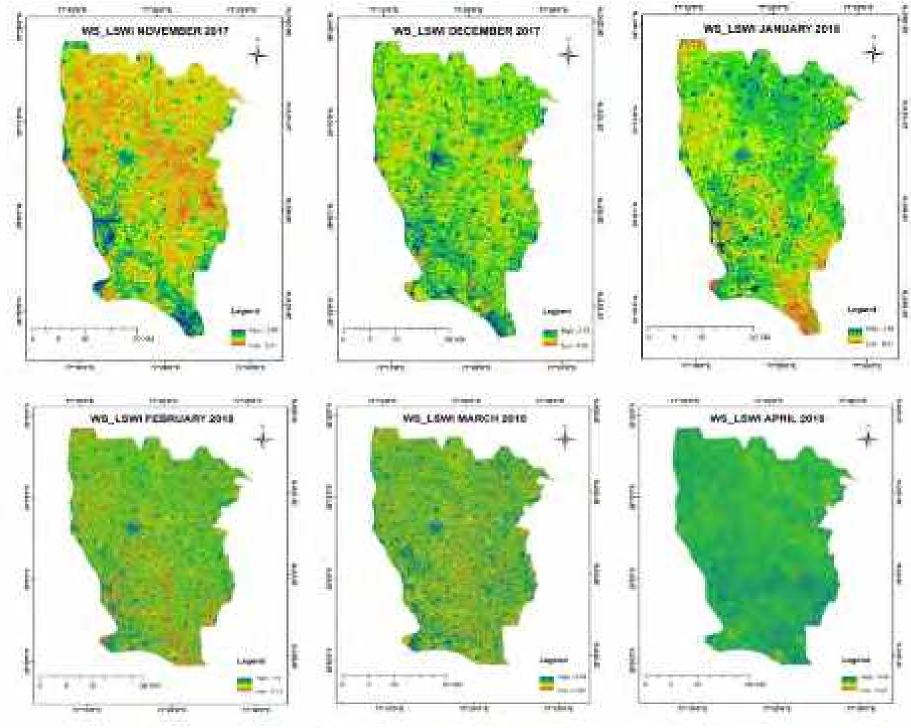


Figure 19: Spatial distribution of WS_LSWI for June 2017 to April 2018

5. CONCLUSIONS

In the present study, remote sensing-based approach was implemented for ET*c* estimation from Bagpath (Western Uttar Pradesh). For this a NDVI rule based classification was done for Kharif and Rabi Seasons by defining thresholds of different classes of the study area and it had an overall accuracy as 86.86% and 79.72% for Kharif and Rabi crops, respectively, with kappa coefficient as 0.81 and 0.712, respectively. Evaluation of NDVI profile clearly captures growing season of sugarcane–wheat and rice–wheat cropping system and enabled accurate mapping of crops in a study area. In Kharif and Rabi season the average value of PET in ranges between 4.41 to 5.91 mm/day and 3.30 to 5.42 mm/day respectively. In rice-wheat cropping system a peak was observed at September and February months with a Kcb value of 1.2 and 1.23 respectively. Kcb temporal profile in sugarcane-wheat cropping system also shows peak in September and February months with a value of 1.24 and 1.03 respectively but the here the peak value of wheat is low it may be due to mixed pixel combination with young sugarcane plantations. The ETc varied from 3.09 to 6.87 mm day^{-1} in June 2017 to April 2018 and the average value of ET for sugarcane is 4.29 mm day^{-1}. Then annual water requirement of sugarcane for our study area is estimated as 2316.6 mm (for 18 months) and 1544.4 mm (for 12 months). The WS_LSWI from June 2017 to January 2018, In June stress was observed with value 0.56 but in September, October it is in decreasing order because of increasing vegetative growth of sugarcane and rice then again in November slightly it was increased and in December value reaches 0.50 because harvesting of rice and old sugarcane plantations. Water scaler values take a dip after December signifying about less water stress as wheat crop growth takes place in January, February and March and again in April higher stress was observed with a value of 0.69 because of harvesting of wheat taken place.

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EXPERIMENTAL STUDY-CLARIFICATION OF THE OPTIMAL PARAMETERS OF THE IRRIGATION REGIME, TAKING INTO ACCOUNT THE DYNAMICS OF EVAPOTRANSPIRATION AND SOIL MOISTURE AT THE EXPERIMENTAL AND LAND RECLAMATION ECOLOGICAL STATION IN GORI MUNICIPALITY (WESTERN GEORGIA)

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ABSTRACT

Rational use of water resources is one of the main directions in water management. In order for water resources to be used as wisely as possible in the public economy, it is necessary to carry out complex measures in the line of water management. Due to the fact that agriculture is the largest water user, the rational use of irrigation water will save both water resources and promote the normal growth and development of agricultural crops.

In order to achieve the above-mentioned objectives, the main goal of our research is to determine the parameters of the irrigation regime in the pilot-improvement ecological point of Gori municipality, taking into account crop water requirements (evapotranspiration), water-air modes, soil characteristics and natural-climatic factors, which ensures optimal use of irrigation water, program crop adoption and maximum maintenance of balance of agro-ecosystems.

Within the framework of achieving the mentioned goal, the following main research activities were carried out: Rheological, physical, mechanical, chemical and water properties of the soil were studied in order to determine the picture of soil moisture dynamics of the selected trial polygon; Climatic conditions were studied to determine evapotranspiration (air temperature, humidity, wind speed, radiation background, etc.); In the trial conditions, the irrigation timings of perennial agricultural crops on the trial field were adjusted according to decades, with proper assessment and consideration of air temperature and rainfall; Under the conditions of different irrigation regimes, the water demand of agricultural crops was determined based on the balance calculation; Based on the results of the research carried out by the research institutes of the European Union, according to the Penman-Monteith method recommended by the FAO, determination of water demand with a reporting attitude.

Keywords: Irrigation regime; Evapotranspiration; Water-soil parameters; Irrigation modernization; Water demand.

1. Introduction

The great role played by irrigated agriculture in raising the productivity of agricultural production is widely known. For the successful operation of irrigation areas, it is necessary to rationally distribute irrigation water and implement the optimal irrigation regime. The existing methods of determining the irrigation regime are local in nature, i.e. applicable mainly for the conditions for which they were obtained through trials. Quantification of specific meteorological conditions does not produce at all or produces unconvincing results. As a result, the irrigation regimes used either reduce the amount of water needed by the plant, thereby reducing the yield itself, or increase it and can become the cause of swamps and secondary salinization of the soil. Currently, the methodology for determining irrigation norms and terms is based on the indicator of yield and plant water demand. Irrigation norms are defined as the difference between the required water demand and the available water supply in the soil, taking into account the rainfall. The amount of irrigation is determined according to the moisture content of the soil, and the timing of irrigation is related to the phases of plant development, relying on the accumulated experience and the intuition of the amelioration operator. Such a method cannot ensure optimal moistening of the soil and its maintenance because the plant's water demand coefficient depends on both the level of agricultural equipment and specific weather conditions.

2. Main Part

Irrigation norms are determined by taking into account the coefficient of specific water demand related to the biological properties of the agricultural crop and the specific weather conditions, which is characterized by a lack

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of air humidity. In the practical realization of this principally correct method, certain inaccuracies are allowed, which lead to serious errors. The biological characteristics of the culture are expressed by the connection of the specific coefficient of water demand with the number of days since the beginning of spring vegetation, i.e., from planting (sowing). Naturally, the growth rate of the plant is not taken into account here, rather it is taken from the average value. In fact, the duration of plant development periods between individual phases of a number of studies varies by tens and hundreds of percent in connection with specific weather conditions (decreased in dry weather and increased in humid weather). Today, the question of the irrigation regime can be subjected to a rational-quantitative basis based on a wide variety of accumulated information about the optimal irrigation regime of agricultural crops. This information was obtained through the generalization of a large amount of experimental data resulting from the determination of total evaporation, evapotranspiration and transpiration of agricultural crops under different natural and climatic conditions. The water requirement of plants is determined by internal and external factors of their development. Intrinsic factors mean the biological properties of plants that have a major influence on the water demand regime.

According to the field research activities we built graphs including relationship between the maximum and minimum temperature (Fig.1), average monthly rain and effective rain (Fig.2) and potential evapotranspiration, which was taken from the pilot site.

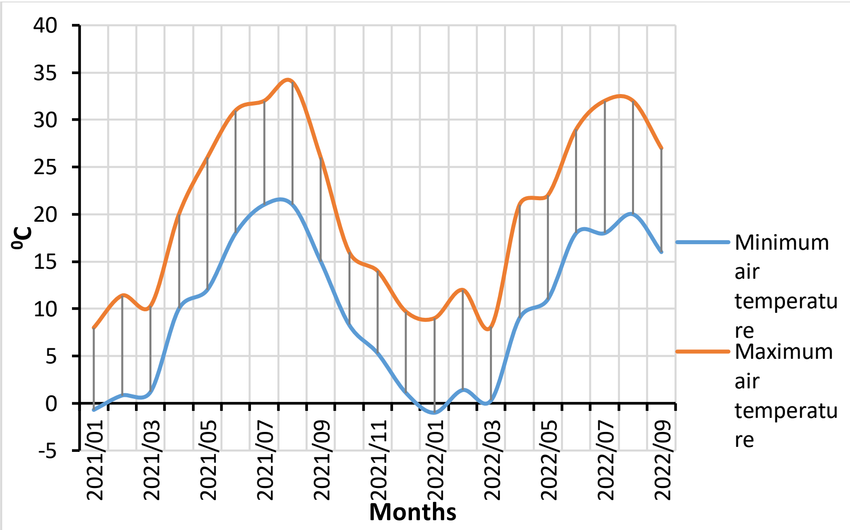

Figure. 1. Minimum and maxim air temperature

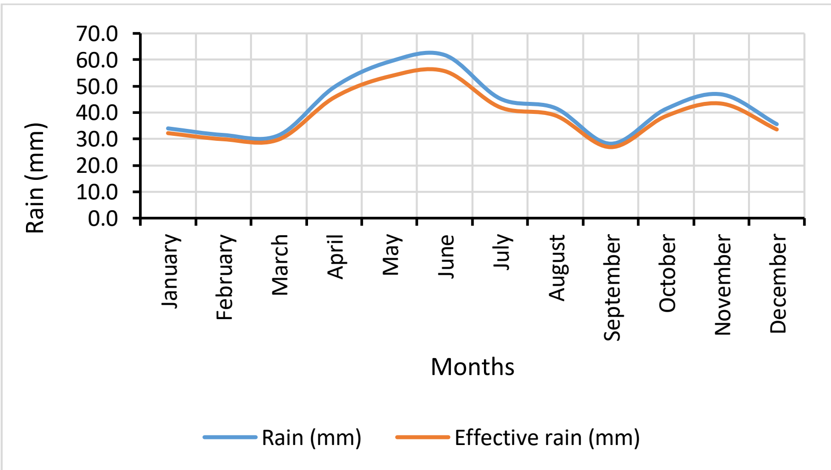

Figure. 2. Average monthly rain and effective rain distribution graphs

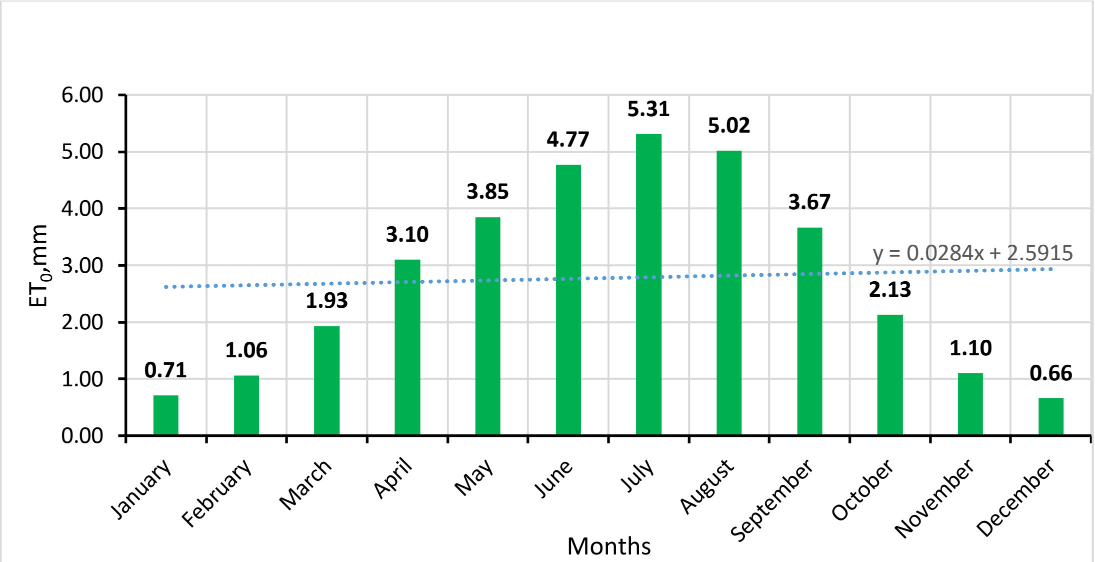

Figure. 3. Potential evapotranspiration

Among the numerous hydrometeorological factors on the dynamic process of the growth and development of agricultural crops, the determination of a complex characteristic, evapotranspiration, the main expenditure component of the water balance, acquires special importance. Transpiration is directly affected by the stages of plant development. The youngest cells of the plant are characterized by high conductivity, and at the next stages of plant development, the conductivity also decreases due to the reduction of protoplasm, as a result of which the movement of water in plants decreases. Water supply by cells decreases and the intensity of water evaporation decreases [1].

According to many researchers, it is not necessary to additionally take into account the influence of soil and agro-techniques on the evapotranspiration process [2,3], but there are opinions of the second group of researchers with a prejudiced opinion, who, based on experimental data, claim that increasing the biological harvest leads to an increase in evapotranspiration [4,5,6, 7,8].

In fact, the amount of evaporated water (taking atmospheric precipitation into account) for the beginning and end of a certain period of time, according to the corresponding soil moisture, will be calculated based on the following equation:

$$E = W_i + \mu P + m + W_e, \qquad (1)$$

where

W_i and W_e, respectively, the reference water amount in the active soil layer at the beginning and at the end of the considered period; P - atmospheric precipitations in the same period; m - amount of supplied water; μ - the retention coefficient of atmospheric precipitation, which is determined by the following equation:

$$\mu = \frac{100\,\gamma H\,(r_{lim} - r)}{P} \qquad (2)$$

where

γ is the volumetric mass of the soil; H - active soil layer; r_{lim} – limited or smallest water capacity of the soil; r - soil moisture at the beginning of the reporting period.

In physical terms, K (water demand coefficient) represents the air deficit and the amount of water consumed per unit. Experimental studies have established that the water demand of agricultural crops changes during the growing season. i. Chkhenkeli [9] obtained the K-coefficient value, which is equal to 0.6 in spring and 0.5 in summer.

According to long-term field experimental data of water demand, the equation for determining water demand is obtained [9]:

$$E = 2.76 D^{-0.193}. \qquad (3)$$

From this formula, it can be seen that as the air moisture deficit increases, the water demand increases.

G. Tughush [10], as a result of the mathematical processing of field-experimental research data, obtained the equation for determining the coefficient of water demand:

$$K = AH^m \qquad (4)$$

Based on this formula, O. Kharaishvili [11] adopted the following approach, which depends on the depth of the active soil layer:

$$D = 2.76D^{0.193}\left(\frac{H_2}{6}\right)^{1.04} \qquad (5)$$

A.M. Alpatiev's [12] method is still very popular, according to which evaporation or plant water demand is determined by the following simple equation:

$$E = KD7 \text{ ან } E = K\sum D, \qquad (6)$$

where

E is water demand, mm; *D* - air humidity deficiency, mm; $\sum D$ - amount of supplied water; *K* - the coefficient of water demand or bioclimatic coefficient, which is determined according to the data of the field experiment, on the basis of the balance calculation.

As is known, the difference between total water consumption (evapotranspiration) and total evaporation is represented by the deficit of water consumption:

$$\Delta E = \mathrm{ET}_0 - \mathrm{ET} \qquad (7)$$

where

ET_0 is the evapotranspiration or water consumption of agricultural culture in the reporting period, mm; ET - total evaporation under natural humidity conditions, mm.

In this equation, according to ET_0, the water requirement of the crop is determined to obtain a high yield.

In recent years, scientists around the world have developed numerous methods for calculating ET_0 from various climate data. Testing this or that method under different conditions is quite a time-consuming process. To solve this problem, FAO developed the following methods for determining ETo [12]: radiation; Penman method; method with evaporator; Refined Penman-Monteith method.

Based on the results of the research carried out by the research institutions of the European Union, the Penman-Montaigne method was recommended by the FAO as the only standard way of determining evapotranspiration, whose reporting attitude has the following form [13]:

$$ET_0 \frac{0.408 \cdot \Delta \cdot (Rn - G) + \gamma \cdot \dfrac{900}{T + 273} \cdot U_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \qquad (8)$$

where

ET_0 is reference evapotranspiration (mm.day^{-1}); *Rn* - radiation on the surface of agricultural culture net (MJm^{-2} day^{-1}); *G* - soil heat flow density (MJm^{-2} day^{-1}); *T* - average day-night temperature (^{0}C); u_2- wind speed at a height of 2 m (ms^{-1}); Δ - slope of the saturated vapor pressure curve (kPa ^{0}C^{-1}); γ - psychometric constant (kPa ^{0}C^{-1}); e_a - actual steam pressure (kPa); e_s - saturated vapor pressure (kPa); (e_s-e_a) - saturated vapor pressure deficiency (kPa).

Alapatiev's bioclimatic method of calculating evapotranspiration, taking into account biological coefficients of total evaporation, has also found great use in irrigated agriculture. This method is based on the relationship between water consumption, air humidity deficit and biological maturity of the irrigated culture, which is expressed by the following relationship:

$$ET_0 = K_d \cdot \sum d; \quad ET_0 = K_t \cdot \sum t; \quad ET_0 = K_E \cdot E_m \qquad (9)$$

where

K_d, K_t, K_E are biological (bioclimatic) coefficients of the crop's water demand, depending on the vegetation period; Σd - sum of average daily air humidity deficit (MB); Σt - sum of average day-night air temperature in the considered period (^{0}C); E_m - maximum possible evaporation (mm).

To calculate the bioclimatic coefficient, evaporation is taken into account, which is calculated according to the air humidity deficit:

$$K = \frac{E_a}{\sum d} \quad (10)$$

And, according to A.R. Konstantinov's method, air temperature and absolute humidity are accepted as meteorological characteristics:

$$K = \frac{E_a}{E_0} \quad (11)$$

According to D.B. Cypris - air temperature:

$$K = \frac{E_a}{t+22.5^0C}, \quad (12)$$

where

E_a - is the actual total evaporation per decade (mm); E_0 - evaporation per decade. It is determined according to air temperature and absolute humidity (mm); t - mean daily air temperature in decade (^{0}C).

Natural moisture ET is the difference between the sum of atmospheric precipitation and soil moisture at the beginning and end of the reference period. In some cases, it is possible to provide additional moisture through groundwater if it is located at a high level. In this case, the total evaporation under natural humidification conditions in any reporting period amounts to:

$$ET = P + (W_1 - W_2) + V_{gr} + V_{sum} \quad (13)$$

where

P is effective atmospheric precipitation (mm); W_1 and W_2 - humidity of the active soil layer at the beginning and end of the reporting period (mm); V_{gr} - amount of ground water used by plants (mm); V_{sum} - sum of surface and underground runoff (mm).

Atmospheric precipitation is the most easily studied indicator among the components involved in natural moisture, and data can be collected through hydrometeorological stations. Determination of soil water supply is also possible through agrometeorological stations.

In conditions of natural humidity, it is appropriate to use V.S. Mezentsev's method to determine total evaporation rates, according to which total evaporation is calculated:

$$Et = E_m \cdot [1 + ((P + W_1 - W_2)/E_m)^{-n}]^{-1/n} \quad (14)$$

where, the parameter n is also determined by the ratio of actual evaporation (under conditions of optimal moisture provision) and maximum possible evaporation.

3. Conclusion

Determining the water consumption deficit is based on decades or months of observations. Deficiency of defined consumption is summed up according to vegetation periods of agricultural crops. As a result of statistical processing of data, 5%, 25, 50, 75 and 95% provision of water consumption deficit is revealed. In addition, provision of 5% water consumption deficit corresponds to a very dry period, 25 to moderately dry, 50 to medium, 75 to moderately wet, and 95 to humid.

As mentioned above, as a result of the analysis of the research results of many scientists, it has been concluded that in the conditions of irrigated agriculture, there are many mathematical models of a theoretical nature for determining the irrigation mode of agricultural crops, but the parameters of the irrigation mode can be determined most accurately using empirical relationships based on direct observations.

Based on the above, specifying the parameters of the irrigation regime, taking into account the characteristics of evapotranspiration and soils, is an actual issue. The natural properties of the soils based on the engineering-melioration evaluation method cannot provide the optimal water-air regime needed by the plant, which is why the plants experience either a lack of air in the case of excess moisture (heavy soils), or an excess of air in the case of a lack of productive water.

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BURIED PIPE, PRE-PAID METER, AND SMART CARD SYSTEM FOR MODERNIZING IRRIGATION SCHEMES IN SOUTH ASIA: EXPERIENCES FROM MUHURI IRRIGATION PROJECT, BANGLADESH

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ABSTRACT

Increasing water scarcity due to growing demand for food and water quality in the densely populated south Asian region has been pushing the water managers in the region to be more efficient in terms of use of irrigation water. Hence, it has become imperative for them to modernize their irrigation systems and improve their water management. This modernization requires both technical and managerial upgrading along with institutional reforms, to improve resource utilization and enhance service delivery up to the farm plots. Towards this end, different technologies are being tried and tested in the different areas. Among these, the buried pipe prepaid meter smart card system technology seems to be a promising one. It is a state-of-the-art technology trusted by Asian Development Bank (ADB). However, the technology demands proper engineering and management interventions including information sensing and transmission technologies. Additionally, it also demands proper financial system engaging private and public sector along with beneficiary stakeholders. Benefits include timely and reliable irrigation services, enhanced agricultural productivity and income, resilience against climate variability, sustained operation and maintenance, etc.

This paper presents some profound insights of the technology based on first-hand experiences of the professionals engaged in modernizing and revitalizing irrigation services in Muhuri Irrigation Project (MIP) through buried pipe and prepaid meters. MIP is a project under Bangladesh Water Development Board (BWDB) located in the middle of the south-eastern region of Bangladesh that has been financially assisted by ADB. The project is situated on the downstream confluence of Muhuri and Feni rivers which are its main water sources. The overall project objective is to reduce poverty, enhance food security through increased crop yields and reduce irrigation production costs. The modernization works in MIP began from February 2016 with the signing of the contract between BWDB and ANZDEC Limited, New Zealand for providing the necessary services of consultancy of Irrigation Management Operator (C-IMO) and are expected to be completed by June 2023. Under hardware activities, the project has rehabilitated 17.75 km of embankment, re-excavated 372.92 km of Khals and constructed six new and rehabilitated seven existing water control structures. Currently, the project is focusing on constructing 850 modernized Low Lift Pumps (LLPs) schemes operated by smart cards and distributing water through a network of buried pipes. Majority of the schemes have already been completed and pre-paid meters have been installed. The smart card system has been found to be very effective in full irrigation charge collection and in giving the farmers full control over the water use. It has also been observed that since the farmers need to make advance payment, they tend to use water more judicially.

Keywords: irrigation modernization; technology; financing.

1. Introduction

1.1 The Original Project

Muhuri Irrigation Project (MIP) of Bangladesh with a design command area of 20,000ha was completed and commissioned in 1986. It enabled dry season as well as supplemental wet season irrigation by constructing the Feni Closure Dam and Regulator to create a reservoir downstream of the confluence of the Feni, Muhuri and Kalidash- Pahalia rivers. The backwaters from the barrage entered the natural channels (khals) and canal network by gravity. From there, it was lifted to irrigate the fields by about 800 low-lift diesel pumps (ADB, 2014).

The project is located between latitude 22.45˚ - 23.09˚ N and longitude 91.21˚- 91.35˚ E in the middle of the Situated on the downstream confluence of Muhuri and Feni rivers originating in India, the command area of the

[1] Team Leader / General Manager, south-eastern region of Bangladesh, adjacent to coastal belt of the Bay of Bengal covered five Upazilas of Feni District and part of Mirsarai Upazila in Chittagong District (Figure 1).Consultancy for Irrigation Management Operation (C-IMO), Muhuri Irrigation Project (MIP).

[2] Project Director, Project Management Unit, IMIP=MIP, Bangladesh Water Development Board (BWDB), Dhaka.

[3] Deputy General Manager (DGM), Consultancy for Irrigation Management Operation (C-IMO), Muhuri Irrigation Project (MIP).

project lies in the flood plains of three flashy rivers Muhuri, Feni and Selonia river networks between the hills of Tripura state in India to the East and the Bay of Bengal to the West.

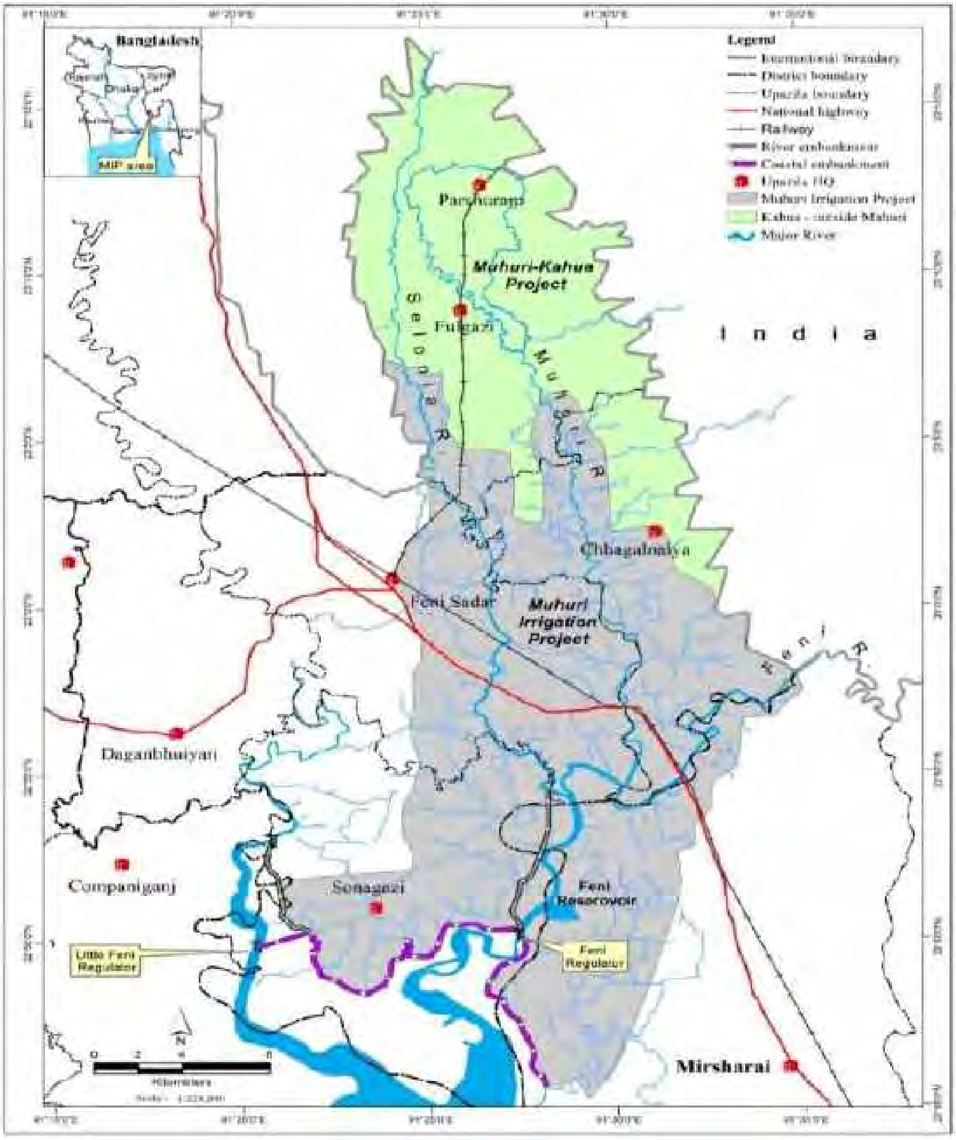

Figure 1. Location map of MIP

1.2 The Rationale for Modernization

Initially, the farmers experienced major improvement in production and were able to cultivate much larger areas with rice. However, the benefits from the project gradually reduced during the last three decades primarily due to the siltation that occurred in the reservoir and khals and the sand, mud and alluvial soil that deposited in the canal beds that came accompanied by the irrigation water. Landslide also occurred in many parts of the canals due to sandy nature of soil. Moreover, the river runoff reduced, and the underground water level went down every year due to the expansion of shallow and deep tube wells for irrigation by farmers in the upstream areas thus reducing water availability for the area. This resulted in the reduction in water flows in the canals. Furthermore, distribution of water through the existing fi+eld channels at the time was wasted due to seepage and evaporation losses and substantial amount of land could not be cultivated. Thus, the project command area reduced to almost about 11,300 ha during the dry season (ADB, 2015).

Additionally, increase in diesel cost combined with low efficiency of the pumps and decrease in rice price further discouraged farmers from cultivating. The pumps for irrigation during the pre-MIP period were largely owned by rich farmers who ran the motors by diesel and sold water to small and medium farmers. The cost for irrigation was high and fixed per bigha (33 decimals). As farmers had to pay a fixed water charge per bigha but lacked the technical knowledge on crop water requirements, they used more water than required for their crops. Consequently, the overall production cost was very high and uneconomic. Many farmers started losing interest in farming and started seeking opportunities elsewhere like working as labours in other cities and aboard (ADB,2014).

In this context, efficient use of water resources with crop diversification/changes in cropping pattern had become essential to obtain food security and alleviate poverty in the area. Hence, the Government of Bangladesh with the financial assistance of ADB launched this project under Irrigation Management Improvement Project (IMIP).

2. The Modernization of MIP

2.1 MIP Modernization Project Objectives

The main aim of the project was to modernize the irrigation system by rehabilitating its infrastructure and replacing them with modern ones that deliver better irrigation services to farmers as per their needs and generate the necessary revenue for its sustainable maintenance, operation and management (MOM).

The overall objective of modernizing the project was to reduce poverty and enhance food security through increased yield of crops and reduced irrigation costs of production (ADB, 2015).

The specific objectives of the project were:

i. To ensure dry season irrigation using surface water through LLPs on re-excavated canal by reducing saltwater intrusion from the Bay of Bengal and the extent, depth, and duration of monsoon flooding.

ii. To modernize the irrigation schemes in the project area for sustainable operation and maintenance by replacing the existing field canals by buried pipes, electrifying the LLPs and introducing the prepaid volumetric metering through smart cards for farmers to receive better irrigation services.

iii. To improve the management of the irrigation schemes in the project area through innovative approaches of modernization and full O&M cost recovery for Level 2 (secondary canal systems) and Level 3 (framers' canal system) infrastructure while the executing agency will carry out O&M of the Level 1 (embankment, regulators, and primary canal system/rivers).

iv. To increase the sustainability of MIP by raising farmers' awareness, institutional strengthening, and effective community participation.

v. To control floods and increase water storage capacity by canal re-excavation and effective and efficient use of available water resources.

The expectation from the project is that the water use efficiency in the area will be increased by 15% assuming that the water use efficiency during baseline condition is 35%. Similarly, in terms of financial sustainability, considering the baseline O&M Needs Based Budget (NBB) to be 20%, the NBB is expected to increase to 90%.

2.2 Project Components and Proposed Interventions

In order to meet the above set objectives, the project was designed with the following four components:

i. Establishment of efficient and sustainable MOM of level 2 and 3 infrastructures

ii. Supervision of the construction of MIP investment contracts

iii. Participatory design of the level 3 distribution system

iv. Agriculture support services, pilot cost recovery and training and awareness

All these four components were proposed to complement each other. Hence, they have been laid out to be implemented in tandem with each other. The project interventions also included rehabilitation of 22.60 km coastal embankment and re-excavation of 460 km khals. It also included extension of electric lines and electrification of all irrigating pumps. Modernization works of the 850 schemes included: setting of buried uPVC pipes; construction of pump houses, header tanks, outlet chambers and vent pipes; and installation of prepaid meter and smart card system.

In an attempt to reduce the irrigation costs, it was also proposed to assess the feasibility of using solar energy in some pilot LLPs. Likewise, the project activities also included farmers' training and demonstration, environmental and social safeguard programs and Gender Action Plan.

3. Implementation of MIP Modernization Project

3.1 Implementation of Modernization Works

The modernization works of MIP began in February 2016 with the appointment by BWDB of FCG ANZDEC Limited, New Zealand for providing the necessary services of Irrigation Management Operator (IMO) as the lead company and BETS and BEL as sub-consultants for the task. This project had some inherent characteristics that made it quite unique and different from the other general irrigation projects in the region. IMO was hired by BWDB in lieu of a team of consultants. The basic difference is that the IMO does not just provide technical assistance as generally done by the consultants, it is responsible for the overall irrigation management of the irrigation system. In MIP, the present IMO called C-IMO is primarily responsible for construction and takes care of all aspects of the irrigation modernization works including design, quality control, construction supervision, etc. as well as MOM of the schemes including operation of all the schemes that are completed by carrying out necessary maintenance and collection of irrigation service fees based on the stipulated rates. The C-IMO is also responsible for providing agriculture support services, training, and pilot cost recovery. In this concern, the C-IMO works directly under the guidance of Project Management Unit (PMU) of IMIP headed by the Project Director. The implementation at the field level is facilitated and supervised by the Project Implementation Unit (PIU) which is the local office of BWDB, and major decisions related to the project are made by the Implementation Coordination Committee (ICC), which is a committee represented by the water users as well as the concerned institutions.

The design works of this project were planned and implemented in a participatory mode. This meant that the project field staff had to identify the potential schemes and confirm them in consultation with the concerned farmers and that the necessary survey and design works were also carried out through discussions with them. The design works involved the design of not just the civil works but also of the electro-mechanical works. Irrigation schemes could not be operated until they are electrically connected. Hence, all the works had be to be carried out in a coordinated way. This participatory modality of design and the need for a coordinated approach for planning the different project components was one of the prime reasons for considerate amount of time it took for the planning and design to be completed in this project.

Consorted effort also had to be put in supervising the modernization construction works as the technology adopted is relatively new for the region. Unlike most surface irrigation systems that convey water through open canals, these schemes had to be constructed to distribute water through buried pipes below the ground and operated by smart cards to precisely control and release water. In this concern, the project team had to give consorted effort on quality control. Firstly, all materials were tested in the laboratory and the contractors were allowed to proceed only after they passed the stipulated technical specification. The Site Engineers and Field Office Managers (FOMs)visited the construction sites from time to time and noted down the measurements of construction works completed. The contractors were asked to submit the measurement sheet on fortnightly basis. The FOMs verified these sheets with their own measurement notes. They also checked the measurements submitted by the contractor. Moreover, random checking was also done by the Chief Resident Engineer (CRE) before finalizing and forwarding the bills. The other positive aspect in the implementation of this project is that there is a lot of check and balance mechanism. After the forwarding of the bills from the C-IMO, it again gets reviewed by the PIU before finally being approved by the PMU.

Finally, the most crucial aspect of this project implementation is its strive for financial self-sustainability. This is an ambition that many irrigation projects in the region want to attend but have not been able to achieve. This project is attempting to collect the required O&M expenditures through service fees collection. The collection process has already started for the completed schemes and the escrow account has already been established and is expanding.

3.2 Challenges of Project Implementation

The project was supposed to be completed in five years. However, it faced many challenges among which the COVID-19 was the major one. This global pandemic affected the project activities in many ways. At certain periods during 2020 and 2021, lockdown was imposed, and movements were totally ceased making it almost impossible to implement and monitor the construction works. Even after the lockdown was lifted, the precautionary measures in place made it very difficult for the works to take pace. Moreover, other factor like delay in timely recruitment and replacement of consultants, delays in contract approval and extensions, logistic support, etc. also caused some hinderances. Due to all these obstacles, the project activities had to be extended and is still ongoing. Presently, it is planned to be completed in June 2023.

The main challenge in the implementation of this project is the multicity of the tasks that needs to be handled in the project. The project involves both hardware and software activities and requires engagement in both the modernization works as well as O&M of completed schemes.

During the implementation of the project, it was also observed that apart from the external factors the project was also challenged by its own inherent characteristics. Firstly, 850 (quite a large number) of schemes irrigating a net area of more than 18,000 ha scattered around the gross command area of 42,000 ha had to be implemented. Hence, the main challenge in the implementation was that the work sites were scattered in 850 different locations under six different administrative units – *upazilas* – five under Feni district and one under Chattogram district. The work at each site had to be the complete set required for each scheme. This in essence meant that the all the work items including civil works of construction of pump house, header tank, vent pipes, outlets, etc. and laying out of buried pipes as well as electro-mechanical and IT works of installation of pump, prepaid meter, starter box, alpha-alpha valve, etc. had to be implemented in all the sites. Hence the modernization works had to be carried out simultaneously at different sites.

The relatively innovative and modern nature of the technology also posed some challenges in the implementation of the project activities. At the beginning, the contractors were not acquainted with the system of buried pipes and were laying the pipes without putting sufficient sand bedding. There was also issue of overtopping from the header tanks and standpipes. Moreover, some of the pumps installed were found to have incorrect rating (ADB, 2022a). In this way, initially there was some hiccups and the project team had to struggle to resolve these. However, in due course of time these issues were resolved.

In this project along with the construction works, the management works also had to be taken parallelly. Due attention had to be provided in operating the completed schemes. This was challenged both by the difficulty of access to all these sites as well as by the lack of proper mechanism of funding for such petty O&M works.

Moreover, the aim of the project of attending financial self-sustainability requires it to garner the necessary O&M expenses through service fees collection. This necessitates the rate of service fee to be set so that it closely matches the requirements (ADB, 2022b;). Additionally, the schemes are operated by smart cards that requires a server and IT inputs which demands the necessary IT knowledge. The project team had to struggle to establish the technical standards (ADB, 2022a) and lacked an ITC expert who fully understands the server linking software and the necessary field operation staff (mechanic, electrician, etc.) to operate and maintain the completed schemes.

3.3 Progress of Works till Date

The status of the project is that most of the infrastructure development part of the modernization works have been completed. The project has rehabilitated 17.75 km of embankment, re-excavated 372.92 km of Khals and constructed six new and rehabilitated seven existing water control structures. Currently, the project is focusing on finalizing the construction of 850 schemes majority of which has already been completed. The main challenge ahead is to set the information sensing and transmission technologies right. This includes installation of pre-paid meters and the electrical and IT connectivity to all the LLPs from the server. This task is on-going. The major task ahead is the MOM of all the schemes which hopefully will be successfully carried out in the coming irrigation season (FCG ANZDEC, 2022).

3.4 Sustainability of Modernization Works

The construction phase of the project is expected to be completed by June 2023 and the project is expected to enter the management phase. For this phase, a Management Irrigation Management Operator (M-IMO) is planned to be formed. A panel of experts (POE) was appointed by ADB to explore the most appropriate way forward for MIP during its management phase. The original idea was to adapt to the Public Private Partnership (PPP) model. However, after extensive consultations, the POE concluded that MIP is not presently mature enough for PPP and it can be revisited later once the project operations becomes financially viable. However, the POE has emphasized that the management of the MIP should ensure that: (i) the risk and responsibilities are properly allocated among the stakeholders (ii) transparent, objective and comprehensive water service tariff regulation mechanism are put in place that ensures cost recovery and provides for a reasonable return on equity and (iii) sufficient operational autonomy is provided to effectively manage its operations, to meet the requirements for operation and maintenance, cost recovery and preserve its business interests, through collection of water service charges or other cost recovery/income generating activities.

As per the Guidelines for Participatory Water Management (GPWM) for schemes over 5000ha, they will be either managed privately through leasing, or management contract or jointly managed by the implementing agency along with local government and community organization. Hence, the role of the executing agency will be continued through joint management while the WMOs will have a high level of ownership in the management (ADB, 2022b).

The POE has suggested the Ministry of Water Resources to take the following actions in terms of the M-IMO:

i) Establish the M-IMO by the end 2022 as a new legal entity operating under a M-IMO Board of Directors to be operational by mid-2023 with the remit to manage the levels II and III infrastructure of the MIP.

ii) Nominate the M-IMO Board of Directors by mid-2022 with a composition that reflects the approach of joint management as set out in the GPWM, with equal representation of BWDB and the WMOs on the board, together with the M-IMO General Manager and representatives from irrigation related organizations.

iii) Develop the constitution, rules and operational procedures of the new M-IMO by including specialist legal advice (selected members of the Board of Directors and the C-IMO can support in the preparation and drafting of the documents).

iv) Facilitate BWDB in engaging the GM of M-IMO and other key personnel through open and impartial recruitment procedures approved by the M-IMO Board. Salaries to be paid by revenue. Personnel from the government can be assigned on lien or deputation if requested by the M-IMO.

v) Facilitate BWDB in preparing a 1-year contract variation for C-IMO up to mid-2023 with tasks to support the completion of the works, commissioning of schemes, start-up operations and support the transition and a first stage handover to a new M-IMO by mid-2023.

These actions are underway and are expected to be accomplished during the project period within which an MOM agreement will be signed between BWDB and the M-IMO where the BWDB will provide bulk water to the M-IMO including ensuring the efficient operation of the barrage, monitoring of river flows, and maintaining of the main coastal embankments and the major khals; and the M-IMO will be responsible the MOM of the minor khals, the pump and pipe systems. The transfer of MOM responsibilities from BWDB to M-IMO will be phased over 5 years from 2023 to 2027 with the aim of achieving full transfer of MOM responsibilities and self-financing by 2028. It is proposed that by mid-2023 the M-IMO should take up overall charge of management and operations and BWDB should maintain all the responsibility for completion, commissioning, and maintenance of all the Level II and III infrastructure until 2027 through maintenance contracts with local companies.

4. Review and Assessment of the Works Carried out under the Project

4.1 Modernization Works

Irrigation modernization is defined as the process of upgrading the irrigation infrastructure, operations and management to sustain the water delivery service requirements of farmers and optimize production and water productivity (ADB, 2015; Renault, 2007). Compared to rehabilitation or upgrading of irrigation infrastructure, modernization is understood as a more far-reaching approach to irrigation performance improvement. It is a long-term adaptive process responding to an array of drivers (from dietary shifts to climate forcing) but which needs to be built-up scheme by scheme where upgrading of the irrigation performance is considered essential (ADB, 2014; Rijsberman, 2001). The process requires a commitment to infrastructural, operational, and institutional adaptation to enable response to current realities and future changes and uncertainty.

Applying this definition to MIP, it very much matches with the MIP project design. Firstly, this project is focused on improving the overall irrigation service performance of the system to optimize production and water productivity. Secondly, it involves upgrading of both the irrigation infrastructure as well as of the operations and management through the deployment of relatively modern technology. Thirdly, the project also includes software activities like institutional reform, capacity building and cost recovery that ensure adaptation to current realities and future changes. All these lead to the conclusion that MIP example is a relatively good modality for irrigation modernization.

4.2 Irrigation Service Performance

Full assessment of the irrigation service performance is yet to be made as the project is not yet complete and all the schemes have not yet been operational. However, judging by the achievements so far, it can be stated that the irrigation service performance has been quite good. Even though only the first lot 81 schemes have currently been operational, the project has already collected more than 31 lakhs 92 thousand Taka in its escrow account. This is a clear indication that the farmers are satisfied with the service delivered by the project otherwise they

would not be ready to subscribe and pay for this service. It is quite sure that this figure will shoot up as soon as more schemes comes under operation. In this concern, the improvement in irrigation service performance has been observed to have occurred mainly due to technology advancements. The water losses in the system seems to have drastically reduced due to the introduction of buried pipe system as it takes the shortest possible (straight) alignment and involves minimum conveyance losses. Moreover, transient losses are also reduced as the schemes are operated by smart cards that allow full control over the water and releases it precisely as planned.
The technology of smart card has been very facilitative in term of service fee collection. It makes full collection possible with accuracy. In fact, prepaid meters arrange for the payment to be made in advance. In MIP, it is estimated that around 70% of the required MOM costs can be met from revenue over the initial 5 years from 2023 to 2027. The shortfall can be met by the government (MOWR/BWDB) in the initial period and reduced when the revenue permits (ADB, 2022b).

5. Experiences and Lessons Learned

This first-hand experience of implementation of the modernization works of MIP has brought profound insights both about the intricacies of the implementation process as well as the pros and cons of the technology of buried pipes, prepaid meters and smart card technology which is relatively new for the region has developed new understandings about this modernization technology.

Some of the lessons learned in the process include the following:

- Participatory design was found to be a bit time-consuming as it required frequent visits to site and several rounds of discussions with the farmers. However, at the end, it was found to pay off as it resulted in the selection of suitable projects.
- The hiccups at the initial stage of the project was primarily due to lack of acquaintance of the people engaged in the construction works with this new technology. It will phase out as they get more acquainted. In this concern, the experience of the project is that it is always better to provide the necessary orientation prior to embarking on the works.
- The experience of MIP has also highlighted the need to timely carry out the electro-mechanical works. In this project, delay in the electro-mechanical works was found to drag down the progress of the whole project. Hence, the different components of the modernization work need to be carried in tandem with each other.
- This technology also requires a server and IT inputs which is relatively innovative for the area. The experience in MIP is that it is important to have a competent IT person in the team and develop in-house competency in handling the software because software issues can be a big hassle.
- It was also experienced that if there are some defects in the construction works, there is a tendency of the farmers to take that as an excuse and connect the pump directly without connecting to the prepaid meters. In this concern, it is imperative to make sure that the construction works are carried out properly and also remain in constant consultation with the water users.
- Commissioning and handover of the schemes can be a bit tricky. The contractor will want to handover schemes as early as possible while there may be some reluctance on the part of the water user unless they are confident with the system. In this context, it can be split into two parts: firstly, by partial commissioning indicating the defects and later the final handing over/commissioning can be done with the testing of successful operation.
- The smart card system has been found to be very effective in collecting 100% irrigation charge from the farmers and giving them full control of when and how much water to use. It has also been observed that since the farmers need to make advance payment, they tend to use it more judicially.

6. Concluding remarks

Considering the relative merits of the technology in the context of the densely populated south Asian region with growing water scarcity it can be expected that this technology will gain more popularity in the days ahead. Hence, this experience of irrigation modernization and the lessons learned can be very useful in enhancing irrigation services both in other irrigation systems in Bangladesh as well as in the other countries in the region. These lessons are expected to contribute to making necessary refinements in this particular irrigation modernization technology as well as in implementing new projects of this nature.

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ON THE RELATION BETWEEN WATER POLICIES AND STRATEGIES AND MO DENIZATION OF THE IRRIGATED SECTOR IN SUDAN

Tarig El Gamri[1] and Adil M. Elkhidir[2]

ABSTRACT

The first national water policy was developed in 1913 to pave-the-way for the construction of Sennar Dam and the Gezira Scheme. The advent of the gravity irrigation in the Gezira Scheme was a huge step towards modernization. The water policies, strategies and plans were then formulated during the period 1952 -1956. They were also revised following the Nile's Water Agreement (1959) and in 2000 and 2007. Relevant legislations include: Water Resources Act (1995), Irrigation and Drainage Act (1990), the Gezira Scheme Act of (2005). However, the national IWRM strategy and water efficiency plan are yet to be developed. Beside that the NAP, NAPA and other Climate Change documents also advocate for the modernization of irrigation. Recent modernization interventions include introduction of modern irrigation systems specially centre pivot system, green houses and hydro-flume in addition to optimization of the cropping pattern. The relatively huge expansion in the use of centre pivot system is attributed to government support and private and foreign investments. The framework program of the Transitional Government (2019) puts renovation of the existing irrigation projects as one of its highest priorities. The recent water strategy (2021–2031) called for the modernization of irrigation. The Strategy is based on three transformative plans. The National Irrigation Transformation Plan (NITP) called for upgrading and modernising 1.1 million ha of existing irrigation schemes, development of 400,000 ha of new irrigation schemes and improving water productivity with at least 50% more crop per drop. Some regional initiatives were also supportive. For instance, the Nile Decision Support System (Nile DSS) of NBI will guide planning for basin future projects e.g. expansion in irrigated agriculture coupled with enhanced water use efficiency. The potential for modernization of irrigation is high provided that political and economic stability is guaranteed, capacity is enhanced and investment is encouraged.

Key words: Irrigation, Modernization, Policies, Strategies, Center Pivot System

Introduction

It is evident that human development has been potentiated by access to fresh water and by the capacities to exploit its' potential as a productive resource (GWP, 2000).

Water deficiencies, quality deterioration and flood influences are among the problems which necessitate greater attention and action. Globally, ten years back it was estimate that more than 1 billion people were deprived of clean water supplies and 2.6 billion people lack access to adequate sanitation Nyambod and Nazmul, (2010). In addition to that approximately 1.8 million children per annum were expected to pass away due to diarrhoea and other diseases related to the ingestion of polluted water along with poor sanitation. The authors concluded that unclean water was the then global second principal killer of children. Recently WHO, (2017) showed the fact that worldwide about 785 million persons are without access to clean water supply and 2 billion people are short of access to adequate sanitation, i.e. the situation is improving. As stated by Ahmed, (2017) in excess of one billion of the global population, predominantly in South Asia and sub-Saharan Africa including Sudan, still practice open defecation. UN Water, (2022) revealed the fact that at present 3.6 billion people are still living with poor quality toilets that deteriorate their health and pollute their environment. In addition to that in excess of 800 children die every day from diarrhoea linked to unsafe water, sanitation and poor hygiene.

Unfortunately, Sudan is among a few countries that witnessed decreasing access to safe drinking water during the period (1996- 2003). This was largely attributed to population growth, political instability and conflicts, low economic growth and inadequate capacity both at the federal and state levels Ahmed, (2017).

Irrigated Agriculture

The area under modern irrigated agriculture is estimated at about 2 million ha out of approximately 84 million ha of arable lands. The Nile system constitutes the source of about 93% of the irrigation water, of which the Blue Nile accounted for about 67%. Gravity irrigation constitutes the principal irrigation method even though pumps serve part of the irrigated area.

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MIWR, (2021) stated that water is the most determining natural resource for expanding irrigated agriculture; since 85% of the Sudan's 84 million ha arable land remains uncultivated. For example, about 50% of the area of the large-scale irrigation schemes (1.2 million ha) is cultivated each year. Similarly about one-third of the area of small to medium scale pump irrigated schemes along the Nile system (900,000 ha) is under cultivation every year. The seasonal flood irrigation schemes viz. Gash, Tokar and Abu Habil are estimated to cover a large total area of about 500,000 ha however; the actual cultivated area infrequently go above 120,000 ha per annum.

Cultivation of cotton on the deltas of the seasonal rivers of Gash and Baraka in early 1860's marks the commencement of commercial farming in the Sudan (REDD+, 2018). Then the Sudan Plantations Syndicate (a British private company) constructed the Gezira Scheme during the period 1911 – 1928 to produce cotton. On a later development and during 1920's privately own pump-irrigated projects were establish on the banks of the Blue and White Niles to grow cotton, fruits, vegetables and other food crops. Afterward a number of schemes were established following the design criteria of the Gezira Scheme including; Rahad, New Halfa and Suki. Elkhidir and Khalid, (2017) stated that production of Sugar in the country commenced with Guneid Sugar Factory 1962 followed by New Halfa, Kenana, West Sinnar, Asalaya and White Nile. The Sugar industry triggered some innovations to improve irrigation efficiencies viz. the use of long furrow, siphon, hydo-flume and the cut-back technique.

A series of multi-purpose dams (irrigation and hydro-power) were constructed on the River Nile and its tributaries: Sinnar 1925, Jebel Awlia 1937, Khasm El Girba 1962, Roseries 1966 (heightened in 2015), Merowe 2006 and Atbara and Setiet 2016. The resettlement projects associated with Merowe Dam are characterized by relatively extensive use of the Center Pivot irrigation system (Mustafa, 2021).

As shown in Fig. (1) Productivity under irrigated agriculture is among the lowest in Africa however, MIWR, (2021) concluded that significant improvement in water use efficiency is attainable. For instance during the 2019/2020 season some pioneer farmers in the Gezira scheme achieved a wheat yield of 6 ton/ha by improving water distribution. Similarly in the Gash delta productivity of the major sorghum crop increased from 0.9 to 2.0 ton/ ha while water consumption was reduced by 30%.

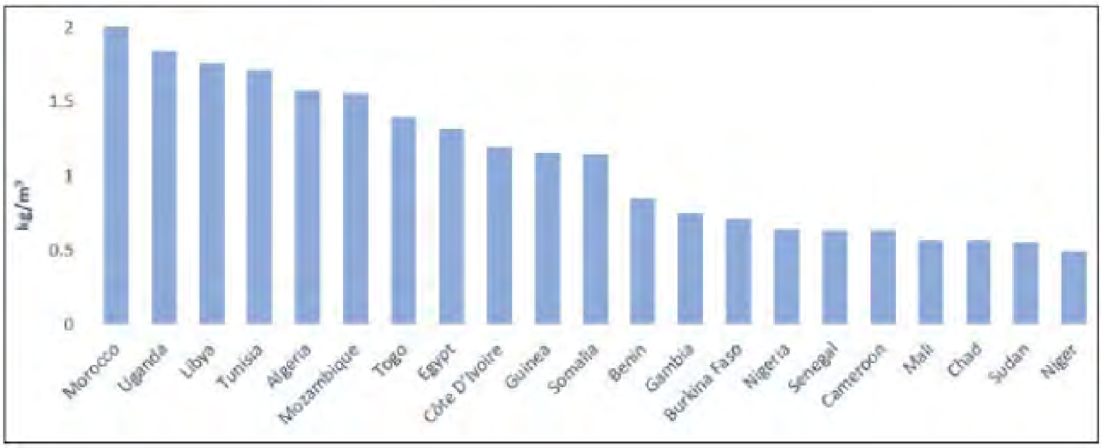

Figure. 1: WaPOR-based productivity of irrigated agriculture in Sudan and other African countries
Source: MIWR, 2021

Saeed and El Gamri, (2008) concluded that very low irrigation efficiencies were reported in some of the major schemes in the country. Ahmed and Eldaw, (2006) attributed that to the unsatisfactory maintenance due to lack of adequate finance. The authors concluded that 20% of total irrigation water may be saved by rehabilitating and developing of the irrigation systems coupled with improvement of water management. In addition to that estimation of the actual crop water requirements and selection of the optimum crop patterns to reduce water losses were recommended.

According to Elkhidir and Khalid, (2017) the following options may be adopted to maximize returns from irrigated agriculture in the Sudan:

- Construction of new projects or extensions to existing schemes.
- Crop intensification to increase the area cropped each year.
- Selection of the most suitable cropping patterns to maximize productivity.

The authors also stressed the importance of developing encouraging national policies and plans.

Evolution of water policy in the Sudan:

The first national water policy was crafted during the colonial era in 1913 to allow for the construction of Sennar Dam and the Gezira irrigation schemes (Adam, 2017a). It's worth noting that non conducive policies prevail through the whole production sectors particularly agriculture and constitutes the basis for the little productivity and loss of competitiveness (El Gamri, 2014). Moreover, HCENR, (2007) attributed the low level of implementation of national strategies and programs to institutional instability and inadequate capacities and investment among others. In accordance with the Water Resources Act 1995, the National Council for Water Resources (NCWR) was created with powers to tackle most of the issues pertinent to water allocation, pollution control, monitoring, information management, economic and financial management, stakeholder participation, flood and drought management, and management of the infrastructural facilities (Adam, 2017b). Activation of the NCWR will pave the way towards IWRM mainstreaming and implementation the author concluded. It's worth noting that state water policies are deficient nonetheless, affected by the federal water policies.

Policy environment before Independence

Introduction of irrigated agriculture using the floodwaters of the Gash River and the Baraka River for commercial farming (in the late 1860s) was one of the first efforts to modernize irrigation in the Sudan. According to Adam and Abdo, (2017) both streams originate from Eritrea and their deltas were used to produce cotton. During the period 1924 – 1926 canals were constructed in the Gash Delta with a view of controlling the floods however, sandstorms made canals impractical in the Baraka. Availability of groundwater encouraged pump irrigation for supplementing deficiencies of flood and cultivation of a second crop. The two schemes were governed by the following Acts:

- Gash Farmers' Act, 1928
- Delta Tokar Farmers' Protection Act, 1943

Extensive surface (gravity) irrigated agriculture commenced during the British colonial era (1898-1956). The then agrarian policy focused on the expansion of cotton production. Introduction of motorized pumping systems took place at the start of the 20th Century, to replace the traditional practices of flood irrigation and water wheel (Sagia). The first national water policy of 1913 was crafted to pave the way for the construction of Sennar Dam and the Gezira Scheme.

The Gezira Scheme which is situated between the Blue Nile and the White Nile is the country's first-born and principal gravity irrigation scheme. The scheme started in 1925 and gradually expanded from then on, to cover an area of around 880,000 ha that is distributed into 114,000 tenancies. The scheme used to be the back bone of the national economy by serving as a major source of foreign currency and of state revenues. Moreover, the scheme maintained the national food security and generated livelihood for the 2.7 million people who reside within its boundaries.

Policy Environment after Independence

During the period 1965 - 1977 the area under large-scale irrigated agriculture expanded from 1.17 million ha to more than 1.68 million ha. The 1980s was an era of renovation, to boost the performance of the irrigation sub-sector. During 1990s, some smaller schemes were approved to the private sector, while the four strategic schemes (Gezira and Managil, New Halfa, and Rahad) remained under government control.

Sudan's National Comprehensive Strategy (1992 – 2002)

Instigated by the severe impacts of the drought cycles of the seventies and eighties the strategy assigned the National Centre for Research (NCR) to study desertification and desert control measures (El Gamri, 2004). Consequently, NCR established the Desert Research Department in 1992 which was promoted into a full research institute in 2003 and specialized research station (Rawakeeb Research Station) (RRS). The research outputs contributed to the modernisation of irrigation as follows:

- Development of low cost building materials for canal lining using locally available aggregates i.e. gravel and water (wadi) transported sand that eliminated seepage losses (El Gamri, 1998). It worth mentioning that seepage losses from irrigation canals at RRS were estimated at about 30% of the abstracted water. Different seepage control techniques were used including cast-in situ and precast linings and production of concrete pipes (El Gamri and A/hameed, 2014). According to Ahmed et al., (2009) adoption of canal lining at Rawakeeb Research Station tremendously improved irrigation efficiencies and crop productivity.

- Mohammed et al., (2011) revealed the fact that introduction of water harvesting and supplementary irrigation greatly improved forage production in the semi desert climates of west Omdurman.

Plate (1): A lined section and field out-let pipe made of local aggregates

National Water Policy and Strategy 1992

According to Adam, A.M., (2017a) this Policy was crafted to compliment the National Comprehensive Strategy (1992 – 2002). The following policy objectives were found to be most relevant to modernization of irrigation:

- Efficient utilization and development of surface and groundwater resources.
- Developing the water sector manufacturing industry to supply water pumps, drilling equipment, pipes, tanks, and spare parts.
- Developing economic criteria for the utilization of water in such a manner as to maintain a balance between the costs on the one hand and the economic and social return on the other.

The Water Resources Act (WRA) of 1995

The Water Resources Act (WRA) of 1995 is considered the main Act dealing with the water resources in Sudan. Other Acts are supplemental to it; like the Groundwater and Wadis Directorate Act, 1998, the Irrigation and Drainage Act, 1990, the Gezira Scheme Act, 2005 (amended 2014). Adam, (2017b) concluded that the Act is designed with emphasis on water development rather than sustainable water management and the Dublin principles were not considered. The Water Law of 1995 delegated states to manage aquifers and watersheds within their respective jurisdiction hence, state water corporations were established. Some states developed state water laws (Gedarif, North Kordofan and South Darfur states). The Interim National Constitution mandated state authorities to manage surface and groundwater waters within the state's jurisdiction. A framework law was prepared to guide states to develop their water laws.

National Water Policy 2000

The policy was formulated by a multi-disciplinary team guided by an international consultant and based on a very wide consultation and engagement of the relevant institutions (Adam, 2017a). The policy embraced IWRM as a mean to alleviate the water management crisis for the first time in the country.

The national IWRM plan

The Ministry of Water Resources and Electricity (MWRE) endeavoured to develop the plan. The process was financially assisted by UNEP with technical support from the Water Resources Commission of South Africa. The initial phase of the process i.e. the vision/ policy development phase was successfully concluded (El Gamri, 2014). Unfortunately, the process was halted due to lack of interest and the suspicious attitude of the then authorities.

Despite the above mentioned draw backs, the National Water Policy of 2000 and the National Plan for Environmental Management of 2007 fabulously embraced the concepts of IWRM. In addition to that the following documents support IWRM: The Interim National Constitution 2005, The Quarter Century Strategic Plan, The National Population Policy and The National Water Supply and Sanitation Policy 2010.

The Quarter Century Comprehensive National Strategy QCS (2002 - 2027)

In 2002 the then government started a process to develop strategic plans for the whole sectors. The idea was unrealistic since by that time the country was facing serious security, economic and political challenges. Beside that the then regime was facing global and regional isolation, economic sanctions and classified as state sponsor terror. The long life span of the strategy is another drawback since the capacity for strategic planning was very weak.

Integrated Water Policy and Strategy (IWPS) 2007

Inspired by the QCS (2002 - 2027) a process to develop a strategy for water resources from 2002 to 2027 was initiated (Adam, 2017a). The vision of the strategy was stated as follows “efficient utilization of water resources to realize the socio-economic development on integrated, balanced and sustainable basis”. As the vision implies modernization of irrigation is well entrenched in the strategy. One of the main justifications to formulate the new strategy is to achieve efficient utilization of water in agriculture. In addition to that the strategy strives at capacity development and stakeholder participation including formulation of Water User’s Associations.

Formulation of the Water Policy of 2007 was grounded on the Transitional Constitution of Sudan of 2005, the water policies of 1977, 1992 and 2000 in addition to the then macroeconomic and social development policies, strategies and plans (Abdalla and Mohamed, 2007). Other directives take account of advancement of the role of women in water resources management and devising incentives for the sustainable use of the resource. However, state water policies are still underway.

Five-Year Strategic Plan (2007-2011)

The strategy constitutes the second phase of the QCS (2002 - 2027) that formulated with accompanying policies to promote adaptation in the water sector. The strategic objectives that were directly linked to modernization of the irrigation system may be summarized as follows:

- Completion of major irrigation projects and improvement of infrastructure.
- Improvement of agricultural production and productivity (more crop per drop).
- Promotion of scientific research, introduction of new technology and capacity building.
- Achievement of water and food security.

Agricultural Revival Programme 2008

The programme gives priority to those projects which benefit the majority of the people in the rural areas such as water harvesting projects which can give quick results within a short period of time.

The programme is based on nine key indicators of success however, the following were found to be most pertinent to modernization of the irrigation systems:

- Creating an appropriate atmosphere for sustainable agricultural development.
- Development and modernization of agricultural systems.
- Development of international partnership specially the component on the transfer of new technologies and management systems.

On the other hand, the strategic objectives which are related to modernization of the irrigation systems include following:

- Increasing the productivity and efficiency.
- Achievement of a national balanced growth with a view to encourage settlement in the rural areas.

Meanwhile the relevant programme policies include:

- Allocate at least 20% of public expenditure for building and modernization of agricultural and livestock infrastructure and advancement of technological innovation.
- Reform existing irrigation schemes and those under establishment
- Ensuring per capita water requirements and provision of irrigation for poverty reduction and food security in rural areas.
- Modernization of irrigation systems including application of agricultural precision technologies.

Despite the great efforts exerted to prepare the Program document it doomed to a tragic failure. The Secretary General of the Program attributed that to the then unstable economic situation, devaluation of the national currency and inflation that has led to increased cost of production (alrakoba.net, 2013).

The National Adaptation Programme of Action (NAPA)

The NAPA consultation process identified priority adaptation activities and needs for the five ecological zones of Old Sudan (before cessation of South Sudan) including the following (HCENR, 2007):

- Introduction of new water harvesting/ spreading techniques making use of intermediate technologies.
- Rehabilitation of existing dams and improvement of water infrastructure.
- Construction of dams and water storage facilities in some wadis, particularly in western Sudan.
- Introduction of water-conserving agricultural land management practices.

Based on the NAPA some projects were formulated and implemented during the period (2010 – 2014) and (2014 – 2017) these projects focused on strengthening the adaptive capacities of small scale farmers and pastoralists with a view of enhancing their resilience to climatic shocks. Central to the project interventions is the introduction of irrigated agriculture especially in Bara locality of North Kordofan State and Fashagha Locatity of the Gedarif State (on the Banks of Atbara River) were rain fed agriculture and raising of small ruminants are the dominant livelihoods.

The regulation of Atbara River due to the construction of the twin dams of Upper Atbara and Setit facilitated installation of small-sized irrigation pumps. By doing so the project created sustainable livelihoods for about 200 farmers, improved the nutritional status of the residents in the area through availing vegetables and the other food crops. In addition to that the projects assisted in bridging the feed gaps during the frequent drought years through the use of crop residues (ARSR, 2018). It's worth noting that irrigated agriculture was also introduced in the upper terraces in Fashagha using solar pumping to harness groundwater and similar impacts were also evident (El Gamri, 2016).

The National Adaptation Plan (NAP)

The prime objective of Sudan-NAP is to minimize vulnerability to the impacts of climate change by augmenting adaptive capacity and resilience building for state and federal institutions. According to HCENR, (2016) the NAP prioritized potential adaptation interventions at the state level. Although it's visible throughout the states plans however, some states explicitly identified the need to modernise the irrigation system as one of their top priorities viz. North Darfur, North Kordofan, Kassala, River Nile, Khartoum and Gezira. Most of the states identified introduction of modern water harvesting and other water conservation techniques as their top priorities.

Based on the NAP some projects were implemented in the various states of the Sudan including the following:

- Enhancing the resilience of communities living in climate change vulnerable areas of Sudan using Ecosystem Based approaches to Adaptation (2018 – 2022).
- The Rural Livelihoods' Adaptation to Climate Change in the Horn of Africa – GEF/ AfDB (2019 – 2022).
- Strengthening adaptation planning processes and capacity for implementation of adaptation actions in agricultural and water sectors GCF/FAO (2020 – 2022).

Policy Environment Post December Revolution 2018

After the Revolution Sudan found a great global sympathy with the change that has been achieved and consequently countries and international organizations showed great interest to resume cooperation with the new Sudan (MCA, 2019). Inspired by the Charter of the coalition of Forces of Freedom and Change, The Constitutional Document and the other initiatives the Ministry of Cabinet Affairs developed a Framework of Work for the Transitional Government. The second priority was on averting economic crisis and laid the foundation for sustainable development including the following sub priorities:

- Development and strengthening agriculture, livestock and industrial sectors
- Rehabilitation of existing irrigated and rain fed projects

Sudan Water Sector Livelihoods Transforming Strategy (SWS-LTS) 2021 – 2031

SWS-LTS is the first strategy that holistically deals with the existing challenges and harnesses the prospects that occur at present to allow for a secure innovative demand to achieve sustainable renovation of the Sudan water sector. The development of the Strategy is based on wide-ranging consultations including national stakeholders and international partners. In addition to that the strategy provides a framework for communication and engagement with other sectors, development and funding institutions and research and academia.

The ambition of the SWS-LTS will endeavour to contribute to the four key priorities of the Government of Sudan as follows: (1) hunger eradication and maintenance of food security for no less than seven million people in rural farming and herding communities, 2) generate attractive and pleasing employment openings for round two million people, especially rural youth and women, 3) coverage of the whole country with safe, sufficient and accessible water supply services, and 4) assist in the maintenance of peaceful co-existence midst all competing water users especially in rural areas. These priorities are greatly analogous to the emphasis of the Sustainable Development Goals (SGDs) 1, 6 and 8.

The Strategy is based on three harmonizing Transformative Plans:

- The National Irrigation Transformation Plan (NITP)
- The National Water Supply Transformation Plan (NWS-TP):
- The National Water Resources Management Transformation Plan (NWRM-TP)

The National Irrigation Transformation Plan (NITP)

The Overarching goal of the TP can be stated as follows: Resilient and sustainable, improved and new irrigation facilities and services for all.

- Transformative package I: Upgrading and modernising 1.1 million Ha of existing irrigation schemes.
- Transformative package II: Development of 400,000 Ha of new irrigation schemes.
- Transformative package III: Improving water productivity with at least 50% more crop per drop.
- Transformative package IV: Inclusive, gender-aware capacity building, institutional strengthening and solution transfer.
- Transformative package V: Facilitative policy, transparent and participatory governance.

Role of Regional Cooperation

Realizing the fact that boundaries for a river basin create a natural unit for water resources management Cap-Net, (2008) advocated for the adoption of integrated watershed management and establishment of river basin organizations (RBOs'). Nevertheless, the legal framework for Nile Cooperation is yet to be approved.

Recognizing the significance of basin (regional) cooperation NBI, (2012) suggested the following basin-wide adaptation measures:

- Coordinated reservoir operation.
- Promotion of basin-wide agricultural trade and with other regions.
- Power and transport interconnection.
- Establishment of a joint mechanism for resource solicitation.
- Joint research.

The National Plan for the Development and Utilization of Water Resources stressed on basin-wide cooperation and improvement of water use efficiency in the irrigation sector to boost water supplies of the country (MWE, 2014).

Moreover, the Nile Decision Support System (Nile DSS) will empower the riparian countries to weigh trade-offs and consequences for basin future projects (NBI, 2012).

Prominent potential 'win-win' benefits include development and trade of clean energy (hydropower), improvement and expansion in irrigated and rain-fed agriculture coupled with enhanced water use efficiency, in addition to water resources conservation and protection of the environment. Other far-reaching benefits of basin wide cooperation include realizing durable regional economic integration and maintenance of peace and security through the basin (NBI, 2019).

Foreign/ private investment

The country was capable of attracting very few mega foreign and national investments in the agricultural sector due to fragile political and economic situation coupled with lack infrastructure and stable investment policies.

Amtaar Investment

Amtaar is a joint Sudan-UAE investment that introduced the innovative floppy sprinkler irrigation system harnessing the groundwater to irrigate an area 6000 ha to produce forage crops and corn. The total annual produce of the project which is located in the Northern State is estimated at about 230000 ton of dry forage that shipped to UAE on weekly basis.

DAL Group

DAL Agricultural Services was founded in 1984 and in 2006 a large modern dairy farm was establish in the Southern part of Khartoum State. To ensure continuous fodder supply Al Waha Farm was established in 2010 with a capacity of 80 million tons using 127 center pivots (https://dalgroup.com/agriculture/). In 2020 an agreement was signed with the African Development Bank to lend The DAL Group $ 75 million to contribute to improving the national food security and to create new job opportunities. In the same year the Group reached an agreement with IHC Food Holding of UAE to establish an agro-business of about 100000 acres in the Northern State with a total cost of $225 million (https://en.wikipedia.org/wiki/DAL_Group.)

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APPLICABILITY OF SWAT AND HEC-RESSIM MODELS FOR WATER RESOURCE OPTIMISATION IN AMBAN GANGA CATCHMENT IN SRI LANKA

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ABSTRACT

Amban Ganga is the principal tributary of Mahaweli River, an example of sustainable water resources development, where ancient irrigation systems are still operating together with modern systems. Kalu Ganga-Moragahakanda reservoirs and Kalu Ganga-Moragahakanda Transfer Canal are constructed within the Amban Ganga catchment to increase the water availability in Mahaweli Basin by retaining unutilized catchment inflows in the Amban Ganga to provide agricultural, drinking water supply, hydropower generation, flood and drought control benefits. However, benefit optimization of multipurpose reservoir systems is challenging while addressing physical, environmental and riparian water rights constraints. Hydrological modelling tools such as SWAT and reservoir simulation models such as HEC-ResSim are convenient for identifying inflows and evaluating reservoir operation patterns for effective and efficient reservoir operation. SWAT was used to simulate the historic catchment hydrology. The model performance is exceptional since the compared model results with the observed flows provided good results for model performance indicators. The HEC-ResSim simulated the Amban Ganga reservoir system to increase the benefits and supply mandatory water demands while minimizing spillages. The HEC-ResSim tool is effective for benefit optimization in reservoirs using user-defined operational rules. This research showed the applicability of the SWAT and HEC-ResSim tools to identify effective and efficient operation plans for increasing benefits from the study reservoir system. The model results show that, on average, 101 MCM/annum of water can be diverted to the Moragahakanda Reservoir from the Kalu Ganga Reservoir after ensuring water security in the downstream irrigation systems. With this diversion, the average hydropower generation in the Moragahakanda power plant increased from 77.1 GWh/annum to 87.2 GWh/annum. This study optimized benefits using reservoir rule curves aiming to increase irrigation reliability since it would directly affect the income of farmers. However, which can be more precisely optimized by considering factors such as national power demand and food security.

Keywords: Water Resource Optimization, SWAT, HEC-ResSim, Reservoir Operation, Water-Right Administration

1. Introduction

1.1. General

Water is paramount and is used for various purposes, such as drinking water supply, irrigation, hydropower generation, and flood control, facilitated by reservoir impoundments with the continuous water supply (Isah et al., 2021). Also, water is becoming a scarce resource as a result of the growing demand due to the rapid growth in the world economy and population, which has created a vast need for optimum utilization of available scarce water resources (Ampitiyawatta, 2020). Furthermore, the recent climate change effects have aggravated water scarcity and pose significant challenges to the efficiency, equity and sustainability of water resource allocation (Deng et al., 2022). In practice, these uncertainties generate enormous challenges for water resources allocation and water quality management; therefore, effective optimization approaches to water management in complex, uncertain conditions are necessary (Meng et al., 2018). Optimization can be described as the maximization of benefits by systematically choosing the function's input value and is generally expressed as the finding of the best available values of some objective function given a defined domain under a set of constraints (Tayfur, 2017). Also, water resource optimization is vital to allocate the available limited water resources for different users based on the need on a priority basis based on the riparian water rights, economic return, power requirement national interests. The application of optimization techniques is most challenging in water resources management due to the large number of decision variables involved, the stochastic nature of the inputs, and multiple objectives. One important example is the multipurpose planning, design, and real-time operation of a system of multiple reservoirs (Datta and Harikrishna, 2005). Reservoir operation and operational decision-making are always complex, involving many decision variables, conflicting objectives, considerable risk and uncertainty (Ayenew et al., 2020) which is conducted according to a set of rules to store and release water depending on the purpose (Abdulateef et al., 2021).

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1.2. Study Area

Amban Ganga is the Mahaweli River's principal tributary and an example of sustainable water resources development, where ancient irrigation systems are still operating together with modern systems for human benefit. Kalu Ganga and Moragahakanda reservoirs are constructed within the Amban Ganga catchment to increase the water availability in Mahaweli Basin by retaining unutilized catchment inflows in Amban Ganga to provide agricultural, drinking water supply, hydropower generation, flood and drought control benefits (ADB, 2014). The primary objective of the Kalu Ganga Reservoir is to release the irrigation water for downstream System F and divert surplus water to the Moragahakanda Reservoir. The Kalu Ganga - Moragahakanda Transfer Canal (KMTC) diverts surplus water to the Moragahakanda Reservoir. **Error! Reference source not found.** shows the Kalu Ganga and Moragahakanda reservoirs with the KMTC.

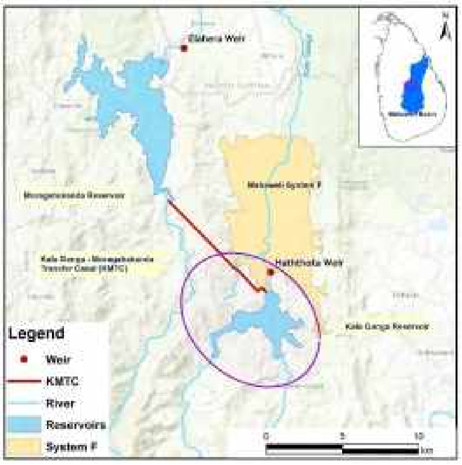


Figure 1. Kalu Ganga and Moragahakanda Reservoirs with KMTC

2. Methodology

2.1. Modelling approach

This study aims to manage water resources in the Kalu Ganga and Moragahakanda reservoirs by minimizing irrigation failures in System F and Haththota Amuna while maximizing hydropower generation at the Moragahakanda Reservoir while satisfying the ecological flow requirements downstream. The study was conducted at daily time steps for 30 years, from 1989 to 2018. This period sufficiently covers several short-term and long hydrological cycles, including dry, average, and wet years. The water resources system selected for the study comprising rivers, irrigation areas, reservoirs, weirs, canals, tunnels, and their connectivity is shown in **Error! Reference source not found.**.

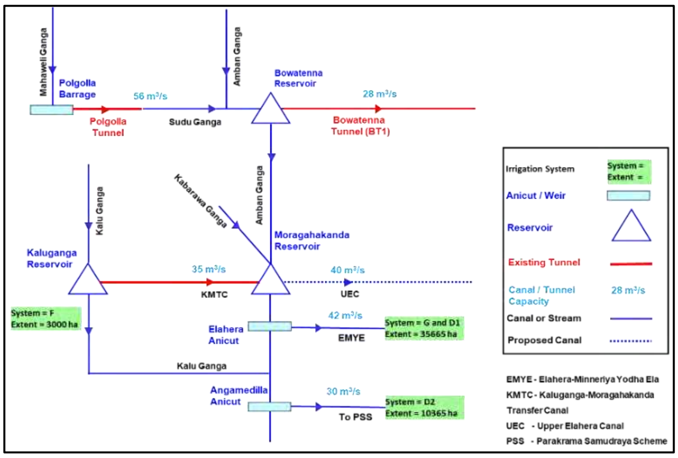


Figure 2: The water-related infrastructure covered in the model

The HEC-ResSim software-based system simulation model developed for this system needs catchment inflows, irrigation demands, environmental flows, diversions, and drinking water demands. The catchment inflows were estimated using a rainfall-runoff model developed based on Soil Water Assessment Tool (SWAT) (Arnold et al., 1998), and the irrigation demands were calculated using CROPWAT (FAO, 2006) software. The environmental flows were calculated using Sri Lanka environmental flow calculator (SLEFC) (IWMI, 2016).

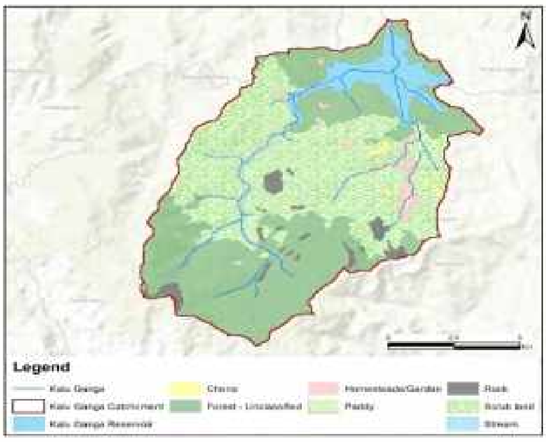
2.2. Rainfall-runoff model

The SWAT is a river basin or watershed scale model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in complex watersheds with varying soils, land use, and management conditions over long periods was used to simulate the catchment hydrology. The physically based and computationally efficient SWAT requires many input data such as Digital Elevation Model (DEM), land use data, soil data, climate data (rainfall and temperature) and measured streamflow data. These data were obtained from different sources given in **Error! Reference source not found.**. In addition, an outlet point for which observed flows are available was identified for model calibration and validation.

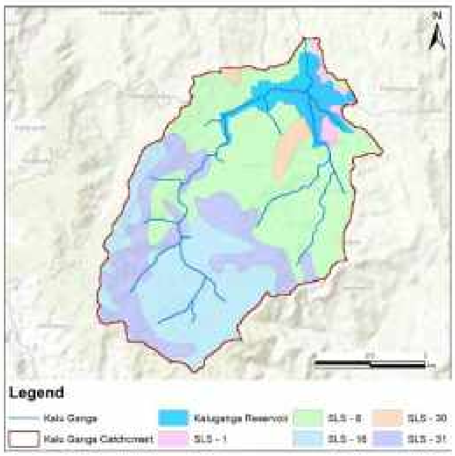
Table 1: Details of collected data

Data Type	Data	Data Source
Topography	Digital elevation model (DEM) (30 m × 30 m)	Shuttle Radar Topography Mission (SRTM) Downloaded from *https://www2.jpl.nasa.gov/srtm/*
Landuse	Landuse map (1:50,000)	Department of Survey, Sri Lanka (Developed in 2013/14)
Soils	Soil map (1:500,000)	Landuse Division, Department of Irrigation, Sri Lanka
Climate	Meteorological data (Rainfall, Temperature)	Department of Meteorology, Sri Lanka
Hydrology	Measured streamflow data (Laggala Gauging Station)	Department of Irrigation, Sri Lanka

Eight land use types and five soil types were identified in the Kalu Ganga catchment, and about 90% of the catchment is covered by forest. The available land use and soil classes of the Kalu Ganga catchment are presented in **Error! Reference source not found.**. A SWAT-based model for the Kalu Ganga catchment was calibrated and validated using the available measured streamflow series at the Laggala gauge station. Subsequently, the SWAT model was used to simulate the catchment hydrology of the Kalu Ganga to obtain catchment inflow series.



(a) Landuse map



(b) Soil map*

Figure 3: Landuse and soil maps of Kalu Ganga catchment

* SLS 01-Reddish-brown Earths and low humic gray soils undulating terrain, SLS 06-Reddish-brown Earths and Immature brown looms, rolling, hilly and steep terrain, SLS 16-Red-yellow podzolic soils and mountain regosoils mountainous terrain, SLS 30-Erosional Remnants, SLS 31-Steep Rockland and Lithosols

2.3. System simulation model

HEC-ResSim (USACE, 2007), developed by the Hydrologic Engineering Center of the United States Army Corps of Engineers, was used to simulate the water resources system shown in **Error! Reference source not found.**. The HEC-ResSim software can be used for simulating a reservoir system for flood management, drought management, hydro-energy generation, irrigation, drinking water supply, and in real-time decision support systems (Calvo and Lucas, 2018; Isah et al., 2021). Also, it can be used to prepare reservoir rule curves (Bekele et al., 2021). The HEC-ResSim comprises a graphical user interface (GUI) to relay information, a computational program to simulate reservoir operation, data storage and management capabilities, and graphics and reporting facilities (Isah et al., 2021). The software consists of three modules: Watershed Setup, Reservoir Network and Simulation for different functions (Ampitiyawatta, 2020). The Watershed setup depicts the general layout of the watershed, the Reservoir Network module controls the input data of the reservoir, and the simulation module is responsible for simulating and calculations related to it (Osroosh et al., 2012). The HEC-ResSim software has been extensively applied in many existing and planned reservoir systems located in many river basins around the world for various purposes. (McKinny, 2005; Mariam, 2012; Olsen and Gilroy, 2013; Belachew and Mekonen, 2014; Jebbo and Awchi, 2016; Calvo Gobbetti, 2017; Ampitiyawatta, 2020; Sulaiman et al., 2021).

2.4. Simulation model development

The developed HEC-ResSim based simulation model is shown in **Error! Reference source not found.**. Reach objects represent Sudu Ganga, Amban Ganga, Kalu Ganga and Kabarawa Oya rivers, while river confluences are represented by the junction tool. The existing Bowatenna Reservoir is included in the model as a storage reservoir with an in-built hydropower facility for the water release downstream. A diverted outlet represents the existing Bowatenna Tunnel. A storage reservoir represents Moragahakanda Reservoir, and a diverted outlet from Moragahakanda Reservoir represents the North Central Province Canal (NCPC). The two existing powerhouses were set to the NCPC outlet and release outlet to the downstream irrigation systems. A storage reservoir represents Kalu Ganga Reservoir, and the KMTC is represented by a diverted outlet from Kalu Ganga Reservoir. The irrigation water users such as Haththota Amuna, Elahera Anicut, and Angamedilla Anicut is represented by diversion tool. The characteristic details of the infrastructure are inputted into the model, and rules were introduced to prioritize the water releases and maintain accurate reservoir operation.

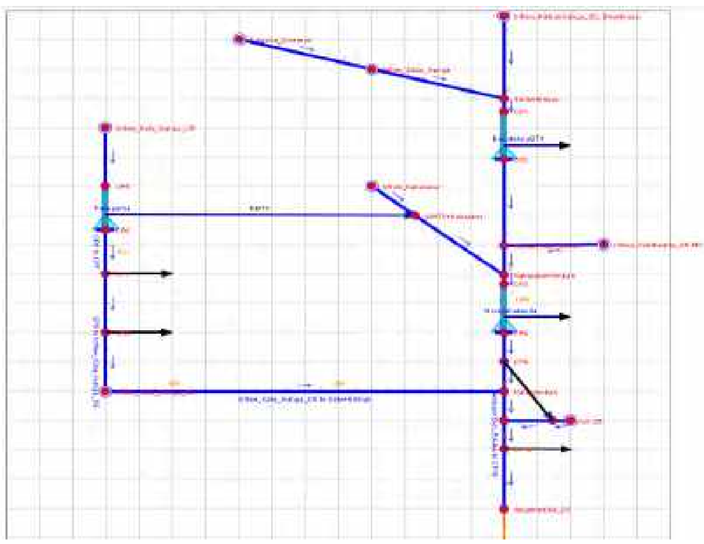


Figure 4: HEC-ResSim based reservoir simulation model

The infrastructure characteristics data of reservoirs, weirs, outlets, canals, reservoir levels (FSL, HFL and MOL), reservoir elevation-area-storage relationships, outlet capacities, canal capacities, operating rules, hydropower generation features such as gate power curves, power plant efficiency, and hydraulic losses were given to the simulation model.

3. Results of the study

3.1. Generation of streamflow data

The SWAT model was calibrated to improve the statistical and graphical relationship between the measured streamflow series of the Laggala gauge station and the SWAT simulated flow series. The selected calibration period is from 01st January 1990 to 31st December 1993, and the validation period is from 01st January 2010 to 31st December 2013. Moriasi et al. (2007) and Ayele et al. (2017) have suggested ranges of best fit for different model performance indicators to evaluate the quality of the comparison of monthly streamflow and those were used in the study. Table 2 presents the performance indicators between the flow series mentioned above.

Table 2: Results of SWAT model calibration and validation (OBS - Observed, SIM - Simulated streamflow)

Model performance indicator	Calibration				Validation			
	Daily		Monthly		Daily		Monthly	
	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM
Average flow (m^3/s)	6.70	6.21	-	-	7.13	6.81	-	-
Annual flow volume (MCM /yr)	211.30	196.06	-	-	225.0	214.8	-	-
Relative Percentage of Bias (PBIAS)	7.22		7.22		4.54		4.54	
Pearson's Correlation Coefficient	0.81		0.95		0.71		0.92	
Coefficient of Determination (R^2)	0.65		0.91		0.51		0.85	
Nash-Sutcliffe Efficiency (NSE)	0.65		0.90		0.48		0.83	

Table 2 reveals that the statistical indices indicate a clear and strong relationship between the observed and simulated flow series.
Figure 5 and
Figure 6 compare the measured flow series of the Laggala gauge with the simulated flow series for the calibration and validation period, respectively.

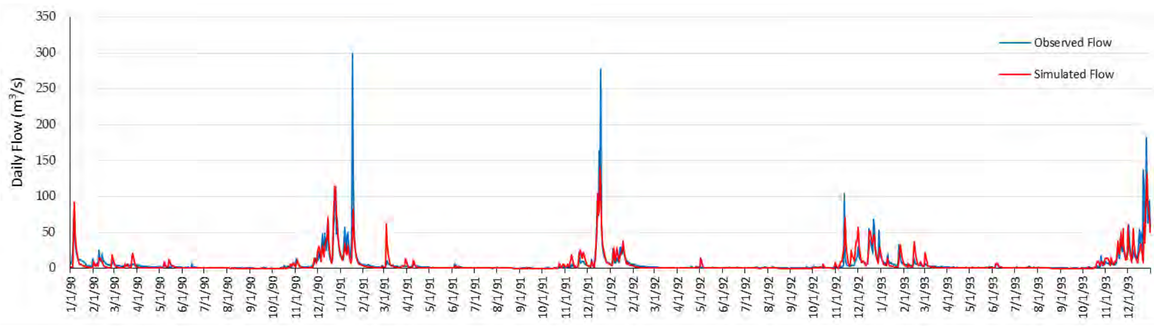


Figure 5: Comparison of daily flows in the calibration period (1990-1993)

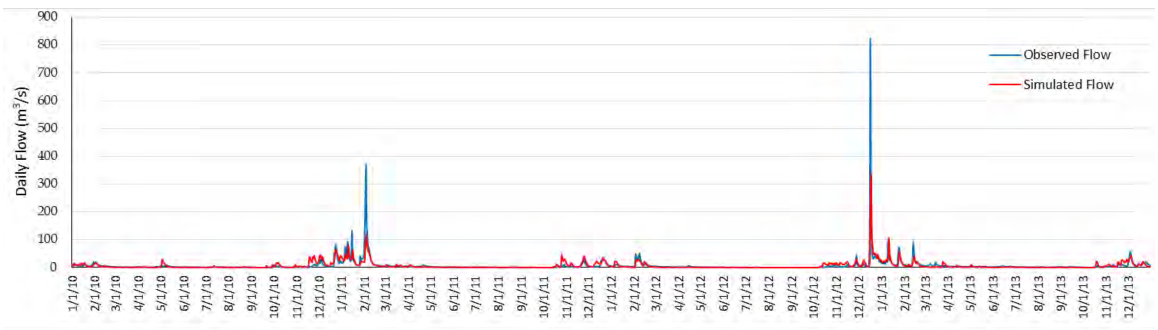


Figure 6: Comparison of daily flows in the validation period (2010-2013)

A solid graphical relationship between the observed and simulated flow series is observed. The model has very closely simulated the base flows, lag-time, and recession limbs of hydrographs but has failed to simulate the peaks, though the dates of peaks are overlapping. The accuracy of measuring peak flows is doubtful in a terrain of shallow river sections and broad floodplain sections. The rating curve of the Laggala gauging station has been developed for low flows, and high discharges with overbank flows have not been measured due to accessibility issues. Therefore, the peak flows are estimated by extrapolating the rating curve done for the river section. The river flow velocity over the flood plain is much lower than that of the river section, while the flow area is much higher than the river section, and hence extrapolated rating curves may give rise to erroneous estimates (PMDSC, 2017).

3.2. Irrigation supply reliability

The supply of the irrigation water requirement of System F operated under the Kalu Ganga Reservoir is prioritized over the diversion to the Moragahakanda Reservoir since those are entirely dependent on water releases from the Kalu Ganga Reservoir. In addition, the supply reliability is prioritized in the HEC-ResSim model by setting a higher minimum operating level (193 m asl) to operate the KMTC inlet to ensure adequate storage in the reservoir for irrigation water supplies (The MOL for irrigation supply is 182.5 m asl). The irrigation supply reliability is checked through a probabilistic approach used by the Water Management Secretariat (WMS) of Mahaweli Authority of Sri Lanka for seasonal operations. These reliability criteria, given in

Table 3 (Acres, 1986; ADB, 2014), assess the percentage of seasonal water deficit quantity in each season and the number of seasons where irrigation deficits occur in each irrigation system. The resultant irrigation supply failure occurrences are given in Table 4. There are two cultivation seasons, namely; Maha and Yala, which are synonymous with two monsoons. Maha Season falls during the "North-east monsoon" from September to March in the following year. Yala season is effective during the period from May to the end of August. The number of irrigation supply failures is well below the maximum level. Therefore, the irrigation supplies to the Kalu Ganga system and Haththota Amuna are considered reliable.

Table 3: Irrigation supply reliability criteria

Failure type	criteria	Max. allowable exceedance	Possible Damage	How to recover
Irrigation failure	>5%	20%	No crop damages	quickly recovered by an effective water management
Significant failure	>10%	10%	Cause minor crop damages	Rigorous water management or reducing the cultivation area
Total failure	>20%	5%	Cause severe crop damages	Reducing the cultivation area

Table 4: Irrigation supply failure occurrences

Irrigation system	Yala season			Maha season		
	5%	10%	20%	5%	10%	20%
Kalu Ganga system	0	0	0	1	1	0
Haththota Amuna	0	0	0	1	1	1

3.3. Optimization of irrigation supply vs. hydropower generation

The irrigation supply reliability and hydropower production (HPP) of the Moragahakanda power plant are conflicting since more water diversion to Moragahakanda would increase HPP but reduce water available for irrigation under Kalu Ganga. In the study, the diversion to Moragahakanda is mainly controlled by setting a threshold water level of the Kalu Ganga Reservoir (rule curve) for KMTC diversion, then water available below that is dedicated to irrigation supply. This assessment shows that (Table 5), when the rule curve level of KMTC increases, the HPP is reduced, and irrigation supply reliability increases, which is represented by reduced failure events. The rule curve level 193 m asl was for the remaining calculations of the study since this project is agricultural, and social justification to the affected farmers is more important.

Table 5: Optimisation of irrigation supply vs. HPP

Rule curve level for KMTC	No. of Irrigation Seasonal Failures (Total failures)	Total HPP in 30 Years (GWh)	Remarks
Base	0	2313	Without KMTC
190	6	2627	Highest HPP
191	5	2626	
192	2	2619	
193	1	2614	Highest Irrigation supply reliability

3.4. Diversion to Moragahakanda Reservoir

The main objective of the KMTC is to divert the surplus water in the Kalu Ganga Reservoir to the Moragahakanda Reservoir after fulfilling the irrigation and environmental commitments of the Kalu Ganga Reservoir. Table 6 shows that the average monthly diversions to the Moragahakanda Reservoir are close to zero from June to October as the Kalu Ganga Reservoir retains sufficient water in storage for its irrigation and environmental commitments.

Table 6: Statistical details of monthly diversion volumes to Moragahakanda Reservoir

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.7
20 Percentile	0.5	0.0	0.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	54.3
Average	19.4	12.5	11.9	14.0	8.7	0.2	0.0	0.0	0.0	0.2	9.2	25.0	**101.0**
20 Percentile	32.5	26.8	22.9	20.5	15.5	0.0	0.0	0.0	0.0	0.0	10.0	43.9	132.5
Max	76.5	43.8	48.8	74.1	66.0	5.3	0.0	0.0	0.0	4.0	61.8	72.7	248.7
STD (σ)	21.9	13.5	14.3	21.6	16.8	1.0	0.0	0.0	0.0	0.8	17.9	21.1	59.4
CV (σ/μ)	1.13	1.08	1.20	1.55	1.93	5.28	-	-	-	3.75	1.96	0.85	0.59

3.5. Hydropower benefits in the Moragahakanda power plants

Three powerhouses exist in the considered reservoir system (under Bowatenna and Moragahakanda reservoirs). The average hydropower output of these power plants is given in Table 7. The annual hydropower output of the Bowatenna plant is not much affected due to the KMTC diversion, but the HPP of the Moragahakanda power plants would be increased by about 10 GWh.

Table 7: Average hydropower generation of each plant

Power Plant	Water Release to	Hydropower Output (GWh / yr)	
		Without KMTC	With KMTC
Bowatenna	Amban Ganga at upstream of Moragahakanda Reservoir	82.4	81.2
Moragahakanda 1A and 1B	Amban Ganga at upstream of Elahera Anicut	53.4	55.2
Moragahakanda 2 and 3	NCP Canal	23.7	32.0

3.6. Reservoir operation behaviors

The variations of monthly storage/total storage of the Bowatenna, Moragahakanda, and Kalu Ganga reservoirs are shown in

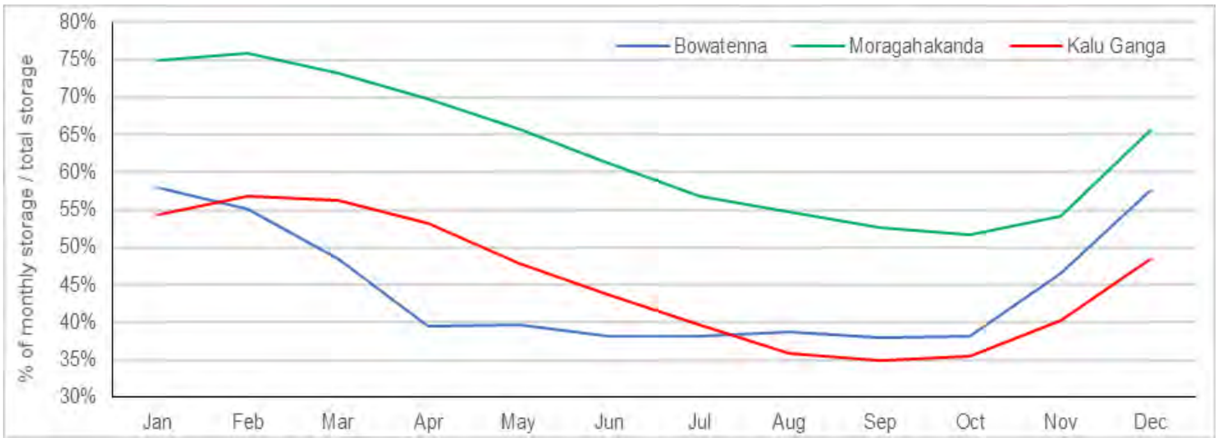


Figure 7. It indicates that the Bowatenna Reservoir storage is comparatively high from October to March (Maha season) and low in the Yala season. This is because the Bowatenna Reservoir has a relatively small storage capacity than the volume of annual inflow and primarily acts as a water distribution reservoir rather than a storage reservoir. Therefore, higher storage occurs during the Maha season due to higher catchment inflow. The Moragahakanda Reservoir indicates that the reservoir storage is comparatively high from December to June. This is because it mainly acts as a storage reservoir for capturing the high catchment inflows that occur in the Amban Ganga and Kabarawa Oya in the Maha season and utilizing them throughout the year, especially in the Yala season. Therefore, the reservoir storage will fall after the North-East monsoon ends in February and begin to rise from October when the 2nd Inter monsoon starts. The Kalu Ganga Reservoir also acts as a storage reservoir for capturing the high catchment inflows that occur in the Kalu Ganga during the Maha season for diversion to the Moragahakanda Reservoir in November - May period and utilize them throughout the year. Therefore, the reservoir storage will fall after the North-East monsoon ends in February and begin to rise from October when the 2nd Inter monsoon starts. In general, both Kalu Ganga and Moragahakanda reservoirs follow the same pattern, but the Kalu Ganga Reservoir is operating at a substantially low storage curve, indicating an underutilization of its storage capacity.

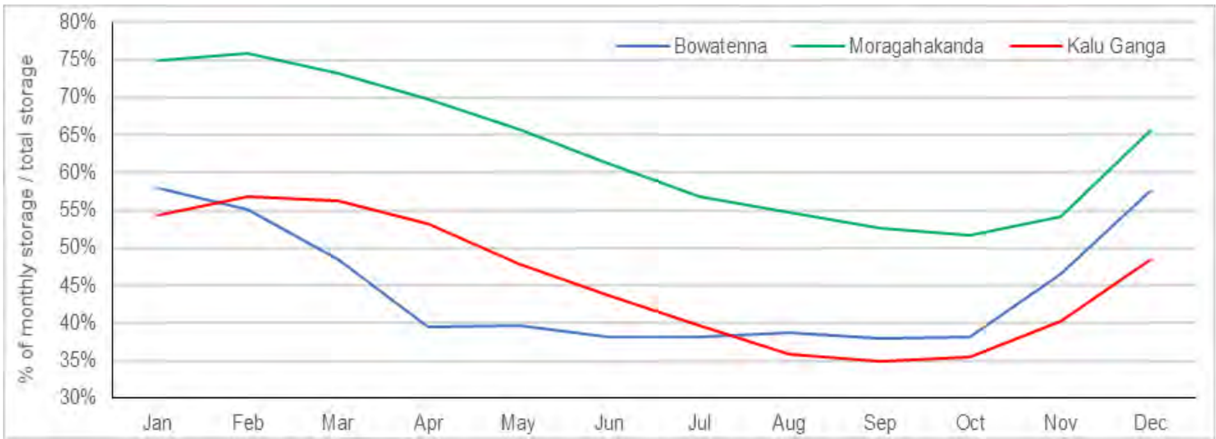


Figure 7: Variation of monthly storage / total storage of Bowatenna, Moragahakanda and Kalu Ganga reservoirs

The simulated daily behaviours of the storages of the Bowatenna, Moragahakanda and Kalu Ganga reservoirs are shown in

Figure 8,

Figure 9 and

Figure 10, respectively. They show that the Bowatenna and Moragahakanda reservoirs have more frequently reached their full storage capacities. However, the Kalu Ganga Reservoir reached FSL only 4 times in the 30-year simulation period, which implies that the reservoir's storage is underutilized.

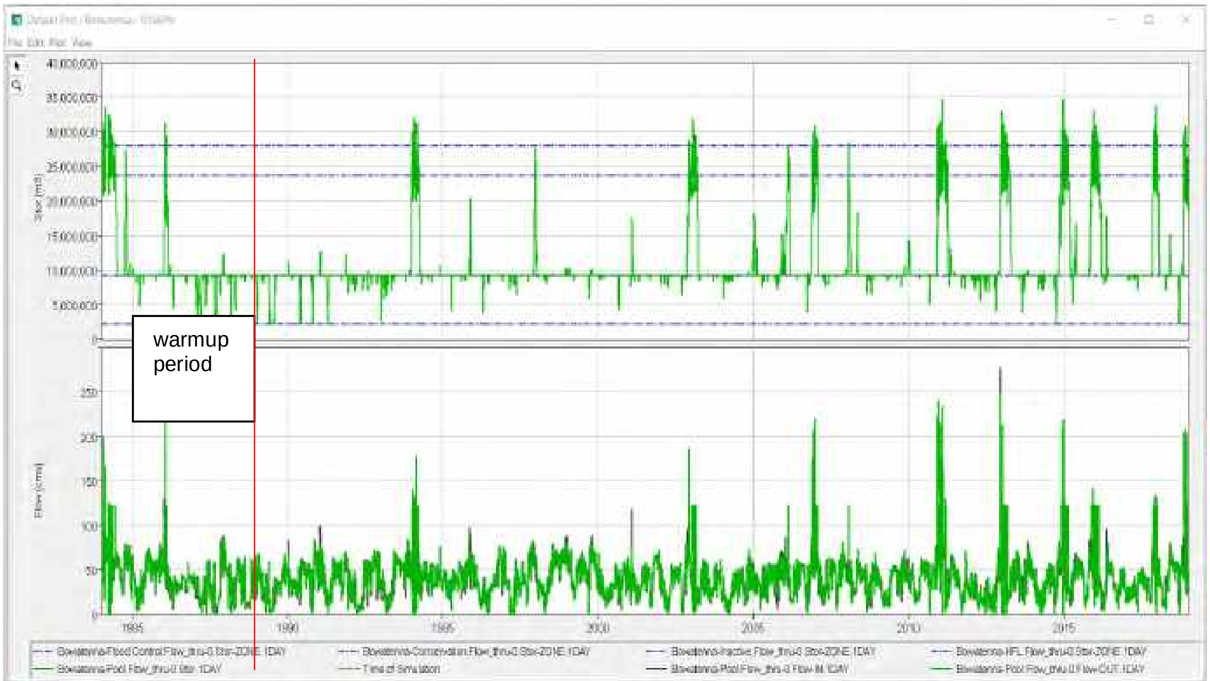


Figure 8: Simulated daily behavior of storage (above), inflows and outflows (below) - Bowatenna

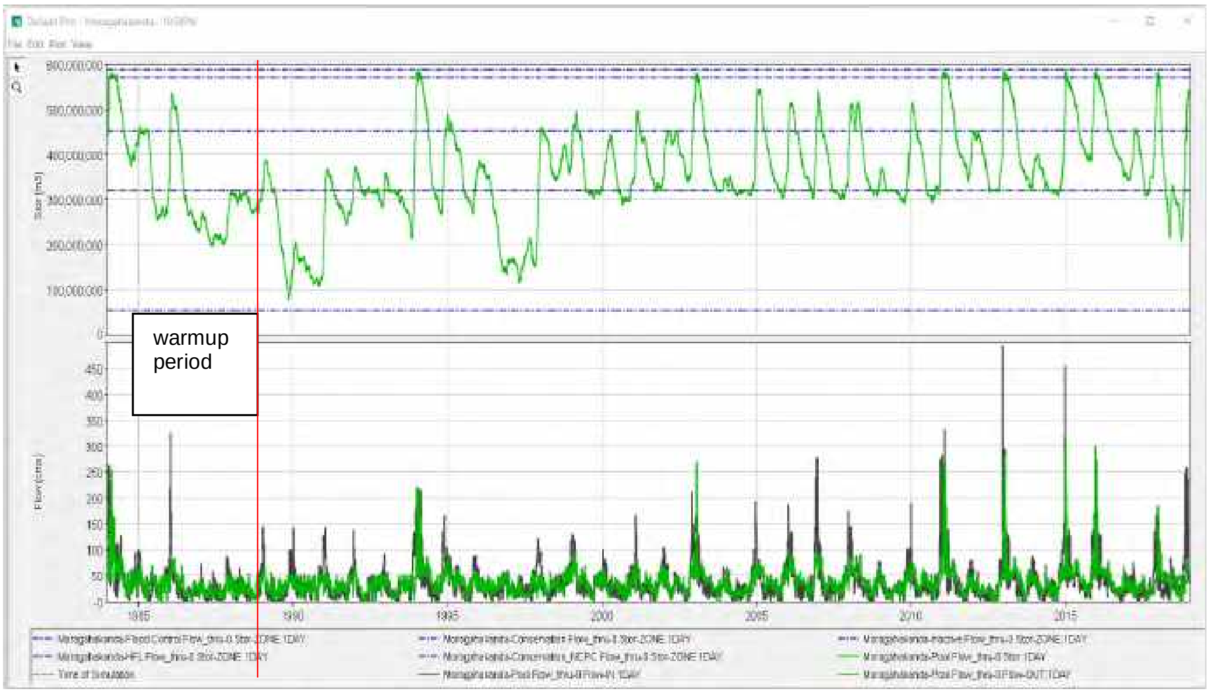


Figure 9: Simulated daily behavior of storage (above), inflows and outflows (below) - Moragahakanda

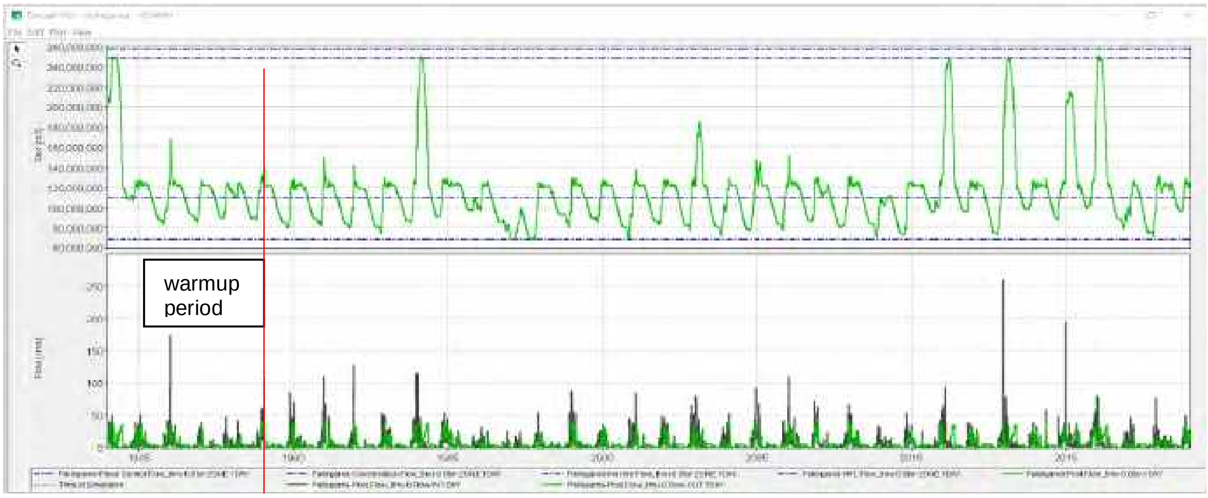


Figure 10: Simulated daily behavior of storage (above), inflows and outflows (below) - Kalu Ganga

4. Conclusions

The HEC-ResSim software was used to develop the reservoir system considered in the study to simulate the impact of the Kalu Ganga Reservoir and KMTC on the existing reservoir system in terms of irrigation water supply and hydropower generation at Bowatenna and Moragahakanda reservoirs under fluctuating reservoir levels and catchment inflows. These practices are presumed to prioritize water supplies to achieve reliable water supplies meeting immediate and downstream demands and environmental criteria. According to the simulation presented in this study, it is proved that HEC-ResSim can effectively simulate single or multiple reservoirs, diversion anicuts (weirs), and different operational scenarios indicating its usefulness in diverse water resource planning and management studies. The study further shows the applicability of the SWAT in simulating the hydrology in the Kalu Ganga catchment to estimate the daily river discharge of the Kalu Ganga at basin and sub-basin levels.

The simulation model results showed that reservoir storage in the Bowatenna and Moragahakanda reservoirs had reached the full supply level with the inflows from the catchment and diversions. However, the Kalu Ganga Reservoir has less frequently reached the FSL of the reservoir, which implies that it has not been optimally used for most of the years. Therefore, the underutilization of reservoir capacity has probably occurred since the Kalu Ganga Reservoir and KMTC are designed to accommodate more water diversions from other catchments (Randenigala, Heen Ganga reservoirs). The HEC-ResSim based model was used to investigate the possibility of optimizing the irrigation supply against hydropower generation from the analyzed water resources system. This study selected the rule curve level 193 m asl from a social perspective to increase the irrigation reliability since it would directly affect the farmer's income. However, that can be more precisely evaluated by adding economic factors such as national power demand and food security.

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DYING LEGACY OF INDIGENOUS IRRIGATION TECHNOLOGIES IN THE MOUNTAINS

Umesh Parajuli[1]

ABSTRACT

Local communities all over the mountains in Central and South Asia have developed indigenous irrigation systems since antiquity. The tradition of self-governing systems and strong community participation are (were) important and common features throughout their management. Local ingenuity and skills have been applied over the ages to develop their technologies. Besides the engineering and agronomic principles, their technologies are also strongly influenced by social, managerial, and ecological considerations

Unfortunately, the legacy of these technologies and their managerial wisdom are dying - partly due to the ongoing socio-economic transformation of the area, and partly due to the non-recognition of these technologies by the development workers - resulting in the introduction of new technologies. However, neither the indigenous technologies are functioning properly, nor the modern-day technologies could replace them.

Of the various types of irrigation systems, this paper focuses on three types of irrigation systems, namely run-of-the-river irrigation found widely in the hills and mountains, water harvesting systems in the trans-Himalayan region, and Karez irrigation in Afghanistan. The paper examines the design management relationship of several infrastructural objects (as technologies) of these irrigation systems and analyses their capacity in undertaking their functions. It then demonstrates how a locally designed and built infrastructural object encapsulates its management functions by applying the basic knowledge of flow hydraulics.

This paper is based on several studies conducted by the author in Central and South Asia. In addition, it also draws heavily on the personal experiences the author gained while working therein. It argues that specific policy provisions should support the revitalization and modernization of these irrigation systems for the benefit of the local community and the nation as a whole

Keywords: Irrigation, technology, mountains, indigenous, modernization

INTRODUCTION

Farmers living in the mountainous areas in Central and South Asia derive their livelihood from farming, which comprises of production of cereal crops, livestock raising, and cultivation of fruit and farm-grown trees. Because of its physiography that constitutes a wide altitudinal variation within a short horizontal distance, the area experiences the greatest variety of climates leading to extreme variations in agroecology, and subsequently availability of water resources

Depending on the natural resource endowments and social organization of areas, farmers all over the mountains have developed indigenous irrigation systems since antiquity that comprise a wide variety of technologies. Many of these irrigation systems are still operating. Local ingenuity and skills have been applied over the ages to develop them. Besides the engineering and agronomic principles, their technologies are also strongly influenced by social, managerial, and ecological considerations. The tradition of self-governing systems and strong community participation are (were) important and common features throughout their management.

Of the various types of irrigation systems, this paper focuses on the run-of-the-river type of irrigation found widely in mountains, water harvesting systems in the trans-Himalayan region, and Karez irrigation in Afghanistan. Sections below describe the features of these irrigation systems

Run-of-the-river types of irrigation systems are widely available throughout the mountainous environment starting from Myanmar in the East to Afghanistan in the West. They exist in both the arid and monsoon climate zones at an elevation of about 2,500m or below the mean sea level. These systems acquire waters from rivers flowing either downhill or along their sides, which are then transported to their command areas through conveyance canals for irrigation. **Figure** 1a presents a typical schematic of a run-of-the-river type of irrigation system. In the arid region, rivers are fed by runoff from snow and glaciers that melt up in the mountains during the spring and summer months when day temperatures are high. While, in the monsoon climate zone, rivers are fed by perennial and or seasonal springs in their watershed, which almost entirely depends on rain in rainy seasons.

The principal physical components of a run-of-the-river type of irrigation system, therefore, include a boulder and brushwood diversion weirs in the source river, a conveyance canal, a network of distribution canals, and related water control structures

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A water harvesting system is a multiple water use system, and they are mostly available in the trans-Himalayan region located towards the north of the high Himalayas in their rain shadow areas. These areas constitute a highly undulating cold desert landscape with altitudinal ranges varying between 2,900 and 6,000 m from the mean sea level. In these areas, agriculture is completely dependent on irrigation, and settlement without a source of water cannot be imagined. In Asia, this area extends from the Tibetan Plateau (China) in the east to the Ladakh ranges of mountains (India) in the West. In Nepal, the Upper Mustang and Dolpo lie in this region.

Snow and glaciers that melt in the upper reaches of the watershed and flow downhill are the main sources of water. This water is then tapped by the local water harvesting system that consists of a gravity canal, intermediate water balancing tank, distribution canals for several uses, and livestock tanks. **Figure** 2 presents a typical schematic of a water harvesting system.

A karez is an ancient irrigation system that draws water from an aquifer located at the base of a hillside. These systems are mostly found in the arid and semi-arid regions in Central Asia at an elevation of about 1,000 m or below the mean sea level. Technologically, it is a sloping horizontal tunnel with a series of well-like vertical adits. At their upstream ends, many of these adits are drilled substantially below the groundwater table to allow water to flow into them. These waters are then transported to an open land surface through karez under gravity. **Figure** 3 presents a schematic of a karez irrigation system.

Focus and objective of the paper

The paper examines the above noted three types of irrigation systems and analyze the design-management relationship of the following three infrastructural objects that were designed and built for multiple functions using local ingenuity and skills.

- Boulder and brushwood diversion weir built across the rivers in run off the river irrigation systems
- Intermediate water balancing tank of the water harvesting systems
- Karez - a slopping horizontal tunnel

The primary objective of the paper is to document the little-known design management relationship of these infrastructural objects and to generate new scientific knowledge in this area for further modernizing these indigenous irrigation systems.

UNDERSTANDING AN IRRIGATION SYSTEM AND ITS TECHNOLOGIES

Irrigation system

An irrigation system refers to both the physical infrastructure of works and the social infrastructure of rules and procedures that enable the acquisition, transportation, storage, and delivery of water to farmers for irrigating their lands. Thus, its design is not only shaped by the engineering and agronomic principles, but also shaped by its organizational and institutional aspects, the people, and the operating environment. A formal or informal community organization, which brings together the users of an irrigation system, manages the system following the agreed rules and regulations.

Irrigation technology

In simple terms, technology refers to the capacity to transform goods into desired things (Vincent, 1997). In irrigation, an irrigation system does control and transfers water through several infrastructural objects to support plant growth. Such an infrastructural object that is designed and built for multiple functions with an intended capacity to transfer irrigation waters for agricultural production is termed here as irrigation technology.

Indigenous technology

Indigenous refers to the point of origin and sources of initiative (Gill, 1992). Indigenous technology can be old as well as new. It may also incorporate the elements of external technologies modified using indigenous knowledge to fit into the local operating environments. They are improvement-seeking and undergo a continuous process of change.

RUN-OF-THE-RIVER IRRIGATION SYSTEMS, AND BOULDER AND BRUSHWOOD DIVERSION WEIR

Figure 1a presents a typical schematic of a run-of-the-river type of irrigation system. It has several components. Of which the boulder and brushwood diversion weir, termed hereafter as BB weir, is one of the main components.

These weirs are constructed by layers of loose boulders with brushwood in each layer. They are temporary in nature. The brush-woods are laid with their leaves facing upstream and the sticks downstream. The boulders increase the stability of the weir by their gravity, while brushwood leaves help deposit sediments upstream by partially sealing the holes between the boulders. **Figure** 1b presents a typical layout and section of a BB weir, while **Figure** 1d presents an example of its picture.

Unlike the conventional engineering design in which weirs are built perpendicular to the main direction of flow (**Figure** 1c), BB weirs are built skewed to the river axis with a much longer crest length (L) across the direction of flow (**Figure** 1b). Pandey (1995) notes that, in the Indian Himalayas, such weirs are usually built at an angle between 30 and 60 degrees to the river axis

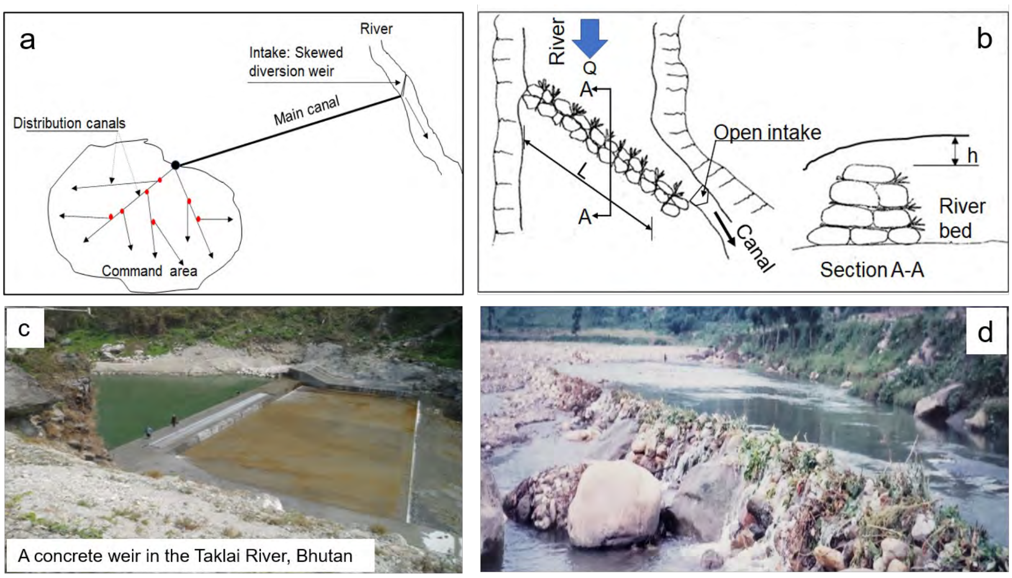

Figure 1. Schematic of a run-of-the-river irrigation system and diversion weirs in rivers

Design-management interrelations

The BB weir is a key infrastructural object of a run-of-the-river irrigation system. It has multiple functions. Of which the following three functions are noteworthy.

- To enhance its stability
- To control and regulate water supply to the corresponding canal
- To maintain river morphology

Sections below describe the efficacy of a BB weir in undertaking its key functions by applying hydraulic principles

Enhance weir stability: It is quite obvious that a weir needs to be relatively stable for undertaking its functions. The stability factor of a weir is shaped by the intensity[2] of discharge that flows over it. Lower the discharge intensity, the impact of the river flow in the riverbed downstream due to the scour holes[3] will be smaller, and subsequently, the weir will be more stable. This hydraulic principle explains why farmers built skewed weirs with a much longer crest length (L) across the direction of flow despite the fact that it increases the cost of construction. Further, larger discharge intensity involves a greater risk of outflanking and damage due to local concentration of flow (Singh, 1972)

Control water supply to the canal: One of the important managerial functions of the weir is to deliver a controlled supply of water into the respective water diversion canal. This function is highly essential because most canals in indigenous irrigation systems have open intakes, and flows through them need to be controlled to avoid unwanted damage to canals and their surroundings.

It is to be noted that flow through an open intake canal is shaped by the water depth (h) upstream of the weir (**Figure** 1b), which in turn is shaped by the incoming river flow[4]. The larger the water depth (h), the higher will be the water flow through the open intake canal and vice versa. However, water depth (h) and its fluctuation with respect to incoming river flow are minimized in the case of a long-crested weir. This means, with a long-crested weir, even if the incoming river flow increases substantially, the increase in water depth (h) will not be that high compared to a situation with a short-crested weir. This hydraulic characteristic of a long-crested weir that

2 Discharge intensity (q) is the flow per unit width of a weir across the direction of flow ($q = Q/L$).
3 Scour depth "R" downstream of the weir is directly proportional to the discharge intensity (q). $R = 1.35\ (q^2/f)^{1/2}$, where f is Lacey's silt factor.
4 The water depth upstream of the weir (h) is directly proportional to the total discharge "Q" but inversely proportional to the weir length "L".

stabilizes water level over it irrespective of variation of incoming river flow explains why farmers built long-crested weirs across the river.

Maintain river morphology: Maintaining the river morphology around the water diversion site is the next important managerial function. This requires that the weir and its biophysical environment around should remain intact. Though the stability factor of a BB weir remains prime consideration in its design, such a weir is bound to fail threatening river morphology when the flow in a river increases beyond the normal flood flows.

To cope with this situation, these weirs are designed and built with a concept of “design to fail”. The concept “design to fail” does not literally mean that they are designed to fail. What it meant is that even if these weirs fail, their parts can easily be reassembled and rebuilt to allow their functioning with minimal damage to river morphology. This concept is close toward higher structural flexibility, which is important in the case of mountains where it might be impossible to construct a permanent diversion weir because of the fragile biophysical environment and water rights downstream. This concept - design to fail - not only reduces the costs of infrastructure but also ensures that the effects of failure on river morphology and costs to the community are controlled. In contrast to the situation depicted above, if a modern concrete weir fails, the effects of failure on river morphology and costs to rebuild such a structure will be much higher

WATER HARVESTING SYSTEM (WHS) AND INTERMEDIATE WATER BALANCING TANK

A water harvesting system (WHS) in the trans-Himalayan region first acquires waters from the snow-fed stream (**Figure** 2a) and transports the same to an intermediate water balancing tank through a gravity canal (**Figure** 2b). The balancing tank then supplies water for irrigation, domestic uses, livestock, and operating the water mill. Except during the winter season when waters freeze due to cold temperatures, this system operates continuously during the rest of the months.

Figure 2 presents a typical layout configuration and components of a water harvesting system, of which the intermediate water balancing tank is its main component. These are small tanks designed to store the available flows through the night. Most of such tanks found in the upper mustang are over 2.5 m deep.

In Nepal, such tanks are locally known as *ching (*Parajuli, U. and Sharma, C. 1998), while D'souza (1997) notes that they are known by the name of *zing* in Ladakh (India). Surprisingly, the local names given to these tanks in both the Mustang and Ladakh areas sound strikingly similar despite their separation by a distance of over 800 km. **Figure** 2c presents a *ching* in the Upper Mustang Nepal.

The tank is equipped with a simple but functional outlet structure built close to its bed (**Figure** 2d). It consists of a rectangular chamber made up of stones, which are sealed with local mud. It is covered by a flat stone about 15 cm thick. A circular hole drilled through the center of the flat stone allows water to flow through it. A long round timber, with one of its ends slightly tapered, is used to open or close the circular hole. This operation is performed from the tank bank. As the tapered end of the timber fits well into the circular hole like a socket, water does not leak through it.

The rectangular chamber is connected to a covered canal, also made up of stone and mud, which leads the flow to an open canal outside the tank. All the joints in this structure are carefully sealed with indigenous aquatic plants like moss and others, which are brought from the higher altitude.

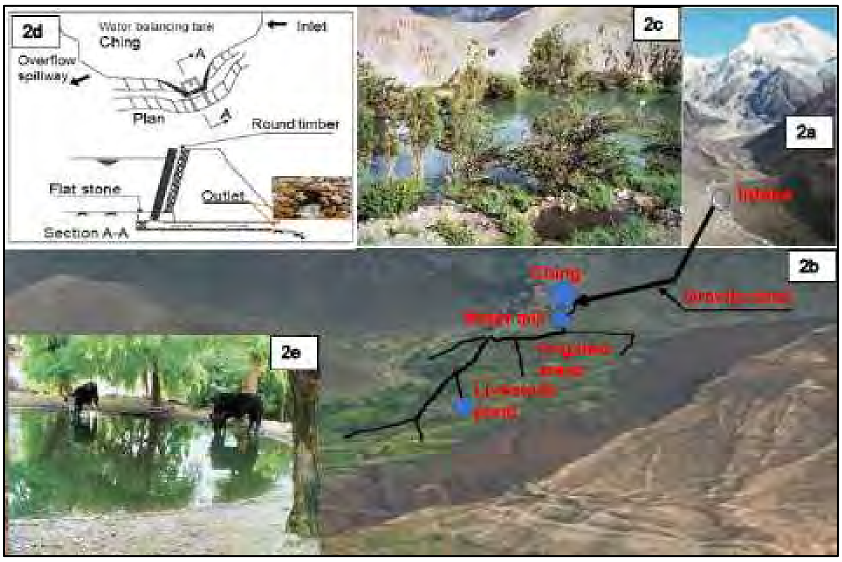

Figure 2. Typical layout configuration and components of a water harvesting system

Design-management interrelations

Though an intermediate water balancing tank is not that common in most run-off-the-river irrigation systems, such a tank is considered to be an important infrastructural object for a WHS in the trans-Himalayan region. Its main function is to regulate and manage water. Sections below explain the efficacy of such a water balancing tank in undertaking its functions.

Flow regulation: As snow and glacier melt slowly through the day and continue till late afternoon, the flow available in a snow-fed stream and corresponding canals increase considerably in the evening compared to that in the morning. In general, the morning flow in a canal during the spring season remains very small (almost negligible for irrigating crops), while the evening flow in the same canal increases by 4 to 5 times compared to the morning flows

In such a situation, it is not practical to irrigate lands in the morning as such small flows seep into the cultivated terraces rather than advancing through them. Unlike this, during the evening when the flow increases substantially, it is too late for irrigation. To avoid this situation, the available incoming flows in the evening and night are then collected in the water balancing tanks for their use next day. The water balancing tank, therefore, re-regulates the fluctuating incoming flows into a steady outgoing flow.

Managing multiple uses of water: Other than supplying water for irrigation, the water balancing tank supplies water also for operating a water mill usually located close to it, maintaining the water level in the livestock pond usually located close to the village (**Figure** 2e), and meeting domestic requirements other than drinking. As water demands for these different uses vary greatly in time and space, the water balancing tank regulates the water supply for these uses as per their demands. In addition, a water balancing tank also maintains the buffer stock of water for the period when the incoming gravity canal does not operate either due to canal breach or heavy snowfall.

Sediment management: Water balancing tanks are designed and built in such a way that their inlet, outlet, and the overflow side spillway are located close to one another, especially on one side of the tank, to minimize the settling distance for the suspended silt (**Figure** 2c). Such a design helps in minimizing siltation in the tank, especially when both the inlet and outlet operate simultaneously.

KAREZ - SLOPPING HORIZONTAL TUNNEL

As noted above, a karez (slopping horizontal tunnel) is an ancient irrigation system that draws water from an aquifer located at the base of a hillside. **Figure** 3 presents a schematic of a karez with a series of well-like vertical adits and an open channel at its end.

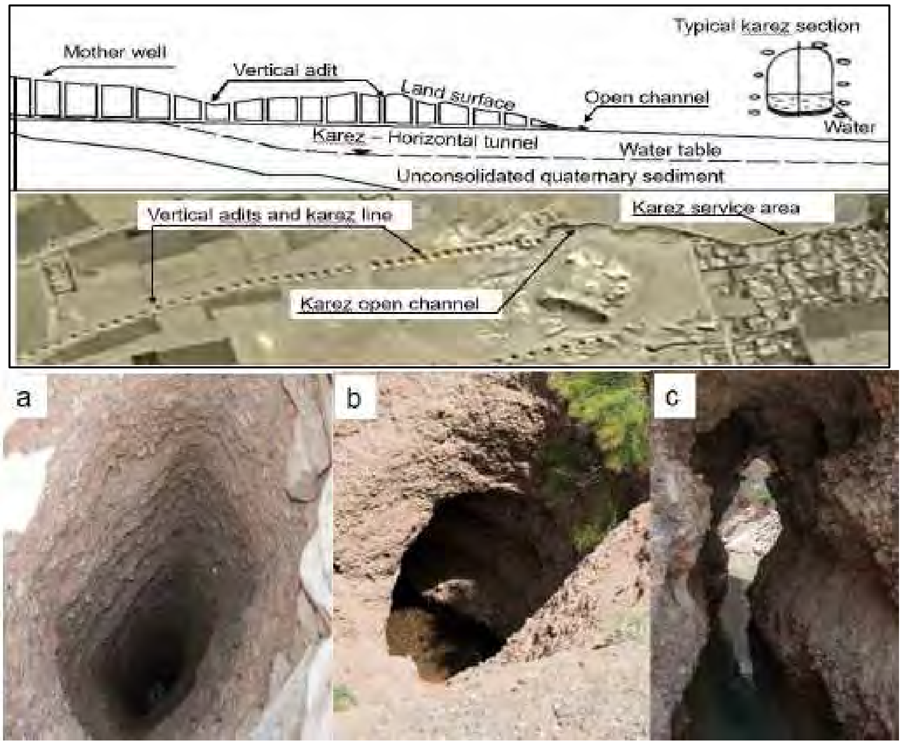

Figure 3. Schematic karez and its Google mas with a series of vertical adits

It is generally believed that Karez was first invented between 500 and 3000 BC in an arid region in central Asia[5] by the people of the Persian Empire (Wessels, J., 2005; Wilkinson, T.J. et.al 2012; Mostafaeipour, A. 2010; Fouache, E. At.al 2010). In this context, Wilkinson, T.J. et.al (2012) noted that at around 1000 BC this area suffered from declining precipitation resulting in the reduction of spring discharge. As a result, villagers started excavating the land surface following the “spring-line” with a view to getting more waters which in turn invented a karez. This hypothesis suggests that karezs were invented sometime around 1000 BC.

The existence of Karezes has been documented from Western China to as far west as North Africa and Spain (Wilkinson, T.J. et al. 2012, Hussain et.al 2008, Mustafa D and Usman, M 2007). It is known by several names in different countries. In Afghanistan and Pakistan, it is known by the name of karez, while in Iran it is known by the name of qanat.

Determinants of a Karez, its development process, and key physical attributes

The existence of karezs in an area is shaped by the water holding capacity of the concerned watershed aquifer, which in turn is shaped by its geological features. Studies suggest that most karezs are found within the gently sloping unconsolidated quaternary mainly, fluvial, alluvial, glacial, and lacustrine deposits consisting of conglomerates, gravels, sand, and clay (Goes, B. et al 2017). In terms of water resources, the functioning of a karez is shaped by the balance between groundwater extractions from the concerned aquifer and its recharge, which in turn is shaped by the precipitation in the area, landscape, and vegetative cover

Regarding its development process, Goes, B. et.al (2017) noted that a mother well is first dug up to 2 to 5 m below the local water level in the well to examine the likely future groundwater level therein and its aquifer characteristics. This investigation provides an indication of the amount of groundwater that can be drained. Thereafter the depth of the mother-well is further deepened so that the first section of the karez when built intersects the groundwater profile for about 200m (McClymonds 1972). Series of vertical adits (**Figure** 3a) and the karez (**Figure** 3b) are then dug to drain the groundwater through gravity. A vertical adit has two functions. First, it provides ventilation to the workers who dig karez well below the ground surface, and second, the excavated materials are pulled out through it. The approximate height and width of a karez are reported to be about 1.25 and 0.70 m respectively (Anderson 1993).

Depending on the landscape and the other local context, the length of a karez may vary from a few hundred meters to several kilometers. Likewise, the depth of the mother well, the spacing between adits, and the likely karez discharge are also shaped by the local landscape and agroecological parameters. **Table** 1 presents the basic physical attributes of 33 Karezs surveyed during 2013 in 6 districts in Helmand Province, Afghanistan.

Table 1. Basic physical attributes of Karezes in Helmand province, Afghanistan

Districts	No of karez	District average				Designed		Average karez slope (%)
		No of adit	Adit spacing	Adit depth (m)	Karez length (km)	Peak discahrge (lps)	Area (ha)	
Kajaki	7	75	39	32	4	30	294	0.0079
Baghran	5	28	27	25	2.4	45	256	0.0104
Musa Qala	6	56	38	29	8	208	273	0.0038
Nauzad	6	59	43	23	4	231	404	0.0056
Washer	5	27	22	25	2	117	217	0.0118
Sangin	4	22	28	23	2	94	280	0.0116
	33							0.0085

Source: Focus group discussions during 2013 (Refer Mott Macdonald, 2013)

Design-management interrelations

Karez is one of the principal infrastructural objects of the karez irrigation system. Its primary function is to transport the waters from the groundwater reservoir to its open end efficiently with minimum hassle for its maintenance. Sections below explain the efficacy of a karez in undertaking its functions.

It is to be noted that both these functions – transporting the water efficiently with minimum maintenance requirements – are related to its flow velocity, which in turn is shaped by its bed slope. Recognizing these hydraulic principles, most karezs are designed and built steeper with a tendency of attaining scouring velocity compared to the theoretically recommended velocity for non-silting and non-scouring conditions. The average

[5] Southern regions of Iran, neighboring parts of Pakistan and Arabia

karez slope (gradient) presented in **Table** 1, which is generally higher than the normally recommended values[6], supports this argument. This situation has the following managerial advantages

- With high velocity, if a small mass of soil falls into a karez, it is easily washed down, thereby requiring less maintenance when the karez is in operation.
- The wetted perimeter and flow area would reduce with higher velocity, which in turn reduces seepage losses from the karez and subsequently increases conveyance efficiency

In addition, it is to be noted that a waterway with a tendency of scouring velocity first gets deeper, and gradually its shape gets stabilized over time. This is because, scouring is primarily caused by the bottom velocity, and at the same mean velocity, bottom velocity is less in deep canal (Chow, 1985). This principle applies to a karez as well, which further supports the hypothesis of building steeper karezs. For this reason, sections of karezs at many locations that were developed over millions of years of operation have deeper and irregular sections (**Figure** 3c).

DISCUSSIONS AND CONCLUSIONS

The paper examined the design and management aspects of the three infrastructural objects - namely the BB weir, water balancing tank, and karez of the run-of-the-river, water harvesting, and karez irrigation systems respectively that were built locally using local materials and applying local ingenuity and skills. Their designs were analyzed primarily from the perspective of their configuration, basic hydraulic principles, and the design basis of their components. The paper then gauged the capacity of these infrastructural objects in undertaking their functions that relate to control and regulation of flow; ease in operation and maintenance; enhancing system efficiency; maintaining environmental safety, and meeting societal requirements. The paper then analyzed their design-management relationship and demonstrated how locally designed and built infrastructural objects encapsulate their management functions by applying the basic knowledge of hydraulic principles.

Though the design of these infrastructural objects may not be highly efficient compared to modern-day technologies, these infrastructures are still wonderful inventions that took into account the basic principles of hydraulics, resource availability, and societal requirements.

However, many of these indigenous irrigation systems are presently dysfunctional (Goes, B. et al 2017, Agrawal and Narain, 1997; and Mott MacDonald 2013[7]). The two main reasons[8] that are worth maintaining here are:

- Introduction of new technologies[9], and
- Weakening social capital as a result of changing socio-economic situation of the area, outmigration, and increasing dependency on external support.

On the technological aspect, though the tube well is identified as one of the leading technologies for the displacement of many indigenous irrigation systems, it is not a cost-effective solution. In this context, Goes, B. et al (2017) noted that a karez irrigation can be operated at about half the operating cost required for operating a diesel-powered deep tube well. Furthermore, there is general recognition that tube wells help only the well-off groups in society, but not the poor and disadvantaged groups. Thus, the societal sustainability of tube well is still in question.

As many of these indigenous irrigation systems are centuries old, they are already regarded as the national heritage of the respective countries. So, these systems need to be protected and made operational. It is understood that the essence of community participation and social capital, which were the basis for managing these systems, have weakened for some years. But such essence should be revived with an appropriate policy outlook. As the self-governing characteristics of these systems still exist and are likely to continue for more years, these systems after modernization will certainly be more sustainable and beneficial to the local community.

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[6] Though the actual bed slope of a waterway and subsequently its flow velocity is shaped by the physical properties of canal bed materials, many engineering guidelines normally recommend a canal bed slope of about 1 in 500 (or 002%) for a small irrigation system (Helvatas, 2014, MacDonald,1990)

[7] A recent study conducted in the Helmand River basin in Afghanistan suggested that 60 out of 240 (25%) run-of-the-river irrigation systems and 26 out of 33 karezs (about 80%) have already become dysfunctional.

[8] Climate change is the third reason, but its impact is common to all types of systems except for a climate resilient system

[9] Some of the new technologies that displaced these indigenous irrigation systems are gasoline-driven deep and shallow tube wells, especially in the arid and monsoon climate zones, the introduction of polyethylene pips in all regions but more in the trans-Himalayan region, and solar-powered pumps.

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ICT TOOL TO IMPROVE AGRICULTURAL WATER PRODUCTIVITY IN UZBEKISTAN

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Extended Abstract

In Uzbekistan, 98% of total agricultural production is produced by the irrigated agriculture consuming 85% of water resources, of which only 20% are formed within the country. The increasing deficit of water due to the climate change, trans-boundary problems and population growth is one of the restricting factors for sustainable economic development. Wide use of water-saving irrigation technologies could be one of the ways to combat these challenges, however currently only 10% of the irrigated lands are under such technologies.

To facilitate introduction of irrigation water saving technologies, rational water use and increased water productivity a Mobile Application TOMCHI has been developed within the framework of the National Water Resources Management Project financed by the Swiss Agency for Development and Cooperation and implemented in partnership with the Ministry of Water Resources of Uzbekistan and Agency of IFAS. TOMCHI in Uzbek language is meaning “drop of water”.

The Mobile Application tool designed as a virtual Extension Service for Farmers providing the following tools: (i) access to comprehensive information on applicable in the local context water saving technologies, relevant legislation and best practices; (ii) estimation of respective costs of certain water saving technique implementation; (iii) feedback mechanism and (iv) platform linking water users with local producers and service providers of available water saving technologies.

Mobile application TOMCH – as a consultancy platform for Farmers/Water Users based on web-portal of the Information Analytical and Resource Center of the Ministry of Water Resources of the Republic of Uzbekistan. Regulatory documents

This unique and innovative application is a first step in introduction of ICT tools in daily operations of the Ministry and its subordinated bodies at basin, irrigation system and irrigation district levels, Water Consumer Associations and farmers to promote improved access to knowledge, data collection and real time information exchange. Along the way are water knowledge portal being developed in partnership with the Information Analytical and Resource Center of the Ministry of Water Resources of Uzbekistan, online water resources monitoring tool, unified national agricultural water scheduling software and development of the comprehensive water management database and decision support system of the Ministry.

Keywords: ICT, water saving technologies, agricultural water productivity, rural transformation, digitalization, innovations, mobile application, database, decision support system, water knowledge portal.

Background: Uzbekistan, Water Resources and Irrigation

Along with Liechtenstein, Uzbekistan is one of the only two doubly landlocked countries in the world. Uzbekistan has an area of 448,920 square kilometers. Uzbekistan lies between latitudes 37° and 46° N, and longitudes 56° and 74° E. It stretches 1,425 kilometers from west to east and 930 kilometers from north to south. Bordering Kazakhstan and the Aral Sea to the north and northwest, Turkmenistan to the southwest, Tajikistan to the southeast and Kyrgyzstan to the northeast, Uzbekistan is one of the largest Central Asian states and the only Central Asian state to border all the other four. Uzbekistan also shares a short border (less than 150 km) with Afghanistan to the south.

Uzbekistan is Central Asia's most populous country. Over 33,905 million people live in Uzbekistan (1 January 2020) – about half of total population in Central Asia. Rural population is 49,5% and urban – 50,5%. The most territory of Uzbekistan has a continental, dry (arid) climate, with little precipitation expected annually (100–200 millimeters). The average summer high temperature tends to be 40 °C, while the average winter low temperature is around −23 °C. Less than 10% of its territory is intensively cultivated irrigated land in river valleys and oases. The rest is vast desert (Kyzyl Kum) and mountains.

In Uzbekistan, available water supply is formed by renewable surface and underground waters of natural origin, as well as by return water of anthropogenic origin. Water resources are mainly formed in the transboundary river basins. Only 9.6% of total runoff of transboundary rivers in the Aral Sea basin is formed within Uzbekistan. In

1) All are representing National Water Resources Management (NWRM) Project in Uzbekistan, funded by Swiss SDC, e-mail: info@nwrmp.uz

other words, Uzbekistan is quite dependent from other riparian countries from the point of view of available water resources.

Figure 1. Map of Uzbekistan

The total land area in the Republic of Uzbekistan is 44,892 thousand hectares, which are divided into 8 categories depending on the purpose and procedure for using land, including: agricultural land; lands of settlements; lands for industry, transport, communications, defense and intended for other purposes; lands of environmental protection, health and recreation; lands of historical and cultural significance; lands of the forest fund; lands of water fund; land stock.

Agricultural lands belong to fertile lands, are considered the main means of national wealth, agricultural production and ensuring food security of the country. The total area of agricultural land is 20,236 thousand hectares, of which arable land is 3,988 thousand hectares, perennial plantings - 383.1 thousand hectares, fallow lands - 76 thousand hectares, hayfields and pastures – 11,028 thousand hectares, other lands – 4,760 thousand hectares. Due to the arid climate, agricultural production is almost entirely dependent on irrigation, and only about 752,900 hectares (18%) of arable land are rainfed.

The current annual water demand of all sectors of the economy is about 64.2 km^3 (see table 1 below). In the long run, the demand for drinking water supply from industry, industry and rural areas will increase, while in irrigated agriculture it will decrease due to water-saving technologies and measures to increase fertility.

Table 1. Actual and prospective water consumption (demand) by sectors in Uzbekistan (million m^3 per year)

Water consumers (by priority)	Total water requirement	including by source		
		Surface Water	Underground Water	Return Water
2018				
Domestic utilities	5320	2200	3120	0
Industry	1885	855	1030	0
Rural water supply	485	415	70	0
Fisheries	640	460	0	180
Energy	770	770	0	0
Irrigated Agriculture	55100	50000	1100	4000
Total	64200	54700	5320	4180
2030				
Domestic utilities	6200	2450	3750	0
Industry	3500	1580	1920	0
Rural water supply	950	810	140	0
Fisheries	640	460	0	180
Energy	780	780	0	0
Irrigated Agriculture	48000	46800	700	500
Total	60070	52880	6510	680

Source: Scheme for the Integrated Use of Water Resources of the Republic of Uzbekistan until 2027. Consolidated explanatory note. Association "Vodproekt" under the Ministry of Water resources of the Republic of Uzbekistan. Tashkent. 2018.

At the level of 2030, the total required water volume for Uzbekistan should not exceed 60.1 km^3 per year. According to the Basin Master-Plans (Schemes), the limit (quota) of Uzbekistan as a whole for the basins of the Amudarya and Syrdarya rivers is 63.02 km^3 / year with a 100% availability. In case of less water availability in dry years, water withdrawal limits are reduced.

The country's total annual water withdrawal in the 1980s was about 66.1 km^3. After gaining independence, Uzbekistan clearly shows a tendency to decrease in water consumption and water withdrawal. In particular, during the period 2011-2015, the total water intake amounted to about 53 km^3 per year (Table 2). However, in 2016-19 it was at a level of about 55 km^3 per year. In the dry year 2021, the water intake was only about 45 km^3.

Table 2. Dynamics of actual water withdrawal from rivers (million m^3)

1960		1980		1990		2000			2010	2018		2021	
Total	Irrigation	Total	Irrigation	Total	Irrigation	Total	Irrigation	Total	Irrigation	Total	Irrigation	Total	Irrigation
30780	27900	64910	55510	56611	58156	53265	35687	56611	44718	54700	50000	45300	39000

It should be noted that the population of the republic from 1980 to the present time has grown from 15 million people to more than 35.2 million people. As a result of population growth, the specific indicator of water consumption per person significantly reduced. An analysis of the use of the water withdrawal limit shows that since 2005 Uzbekistan receives water on average 85.0%, and in dry years, like 2008, 2011 and 2021 about 70-75% of the total annual limit.

Present-day irrigated farming remains one of the most important economic sectors in Uzbekistan, which provides 17% of GDP; but what is the most significant that it is the factor of social stability under ensuring 30% of employment (as of 2021). Thanks to understanding of the social value of irrigation and the wise state policy in the water sector over years of independence, Uzbekistan has managed to maintain its irrigation potential.

Figure 2. Trends of Irrigation Development in Uzbekistan (area, 000' hectares)

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In Uzbekistan, a total length of the inter-farm and on-farm irrigation networks amount to 27,868 km and 154,957 km, respectively. 60 percent of inter-farm canals and 77 percent of on-farm canals have an earth (not lined) channel.

The area of more than 2.2 million hectares is irrigated by pumps that consume electricity of 7,5 billion kWh a year. The following examples show a scale of pumping irrigation: the Karshi Pumping Cascade lifts 200 m^3/sec of water up to 157 m essentially for irrigation of 335,000 hectares in the Karshi Steppe; a cascade of pumping stations along the Amu-Bukhara Canal lift 216.4 m^3/sec of water up to 115 m for irrigation of 315,000 hectares. The Ministry of Water Resources is funding operation and maintenance of 1687 pumping stations where 5284 pump units with total annual capacity of 59.6 billion m^3 of water.

On October 9, 2019 there was released Decree of the President of the Republic of Uzbekistan "On measures to further improve the water management system". By this document priority areas under leadership of the Ministry of Water Resources by the end of 2022 were identified:

- Timely and high-quality development of the Concept for strategic development of water resources in 2020–2030;

- Phased (starting from 2020) implementation of mechanisms for covering a part of the operational costs for the delivery of water by water consumers;

- Bringing the share of land irrigated using water-saving technologies to at least 10 percent of the total area of irrigated land by actively assisting agricultural producers to introduce water-saving irrigation technologies, expanding the production of modern irrigation systems by attracting private investment;

- Institutional, technical and technological development of water management, integration of science with production in this area.

Mobile Application TOMCHI

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Mobile Application TOMCHI is software designed to work using smartphones and other mobile devices. It works in smartphones running on Android and iOS platforms. For smartphones running on the Android platform, the application can be downloaded from the Google Play Market, and for smartphones running on the iOS platform from the Apple Store (Figure32).

Figure 3. Mobile Application TOMCHI (just use the Google Play Market)

Mobile Application (MA) TOMCHI includes information on modern water-saving technologies for irrigation, such as drip, sprinkling and subsoil, also water-saving methods for traditional for Uzbekistan furrow irrigation, such as alternating irrigation and dry inter-row irrigation, short-furrow irrigation and variable-sprinkler irrigation. The MA suggests to use various technical means for furrow irrigation widely used in Uzbekistan, such as the use of flexible irrigation hoses, discrete irrigation, irrigation using furrow-shielded polyethylene film and the use of moisture-retaining hydrogels.

The MA (Interface in Uzbek language) provides information on methods for determining the irrigation time/scheduling for different crops, information on field activities/cultivations that contribute to water conservation. Also, the MA provides information on local manufacturers who produce water-saving irrigation systems, information on service providers for the implementation of water-saving irrigation systems, as well as information on incentives for the implementation of water-saving irrigation systems supported by Government of Uzbekistan.

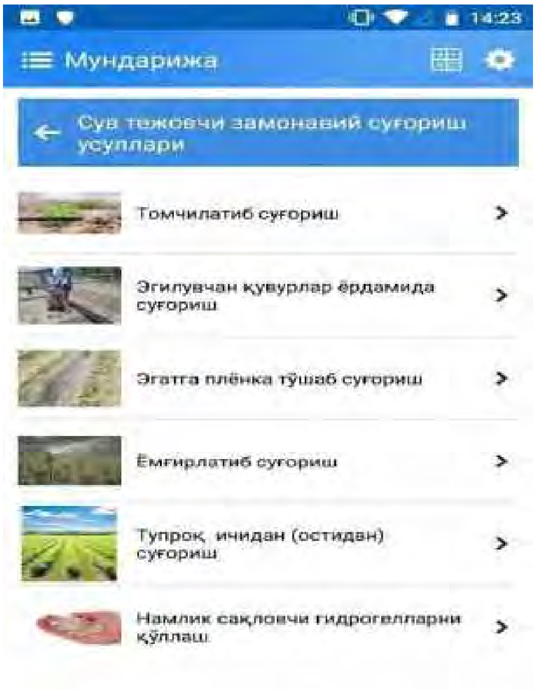

Figure 4. MA "Tomchi": Section "Modern Water-Saving Irrigation Methods"

The sub-section "Modern Water-Saving Irrigation Methods" provides detailed information on modern advanced water-saving irrigation methods, such as drip irrigation, sprinkler irrigation, subsoil irrigation, the use of flexible polyethylene hoses and films for furrow irrigation, irrigation using water-retaining hydrogels (Figure 4).

Mobile application TOMCHI includes a number of sections. The first one is section "Water-saving irrigation methods", which consists of two sub-sections:

- "modern water-saving irrigation methods";
- "water-saving methods of traditional irrigation".

Thus, the sub-section focuses on the most popular technologies of advanced irrigation which in recent years have been actively stimulated by the government for agricultural irrigated lands in Uzbekistan. It also provides information on the use of moisture-retaining hydrogels for the efficient use of water (soil moisture conservation) when growing crops.

Each part of the sub-section describes in detail the presented irrigation method, its advantages, the conditions for their applicability, the constituent elements of the irrigation method, the rules for the design, specifics of construction and operation of certain irrigation system. The sub-section "Water-Saving Methods of Traditional Irrigation" provides information on water-saving methods of traditional surface furrow irrigation (gravity irrigation), in particular, water-saving methods (irrigation by alternating water and dry rows, irrigation using short furrows and irrigation with a variable stream).

Section "Enterprises". This section provides information on the main local manufacturers who produce elements of water-saving irrigation systems. The section includes detailed information and contacts of the main manufacturers / factories, design organizations and service providers. The section also provides examples of the most successfully implemented in local conditions technologies and results and lessons from functioning water-saving irrigation systems.

Section "Governmental Incentives to Support Water Conservation". The section highlights governmental efforts to stimulate wide practical introduction of water-saving irrigation systems, in particular drip irrigation systems. In Uzbekistan, farmers (agricultural producers) using traditional irrigation methods to grow crops usually do not pay for water, but pay a Unified Land Tax. For farmers using water-saving irrigation technologies, in particular, introducing a drip irrigation system, a privilege has been established by Government for exemption from the payment of a Unified Land Tax for a period of 5 years.

The section also provides information on the provision of soft loans and subsidies (in the amount of 50% of the installation cost) to farmers who are going to install drip or other water-saving irrigation methods. At the same time, the information in this section is constantly updated in the light of new decisions by the government to promote water conservation.

Section “Setting Schedule of Irrigation”. This provides information for certain farmer on determining the timing of irrigation for crops based on a visual assessment of changes in soil conditions and crops grown at the particular field. That is done on the basis of instrumental measurements of changes in soil moisture, which farmer should put into MA. The section also provides recommendations on methods for assessing changes in soil moisture using various laboratory devices, such as thermostats, remote sensors and cameras to determine the suction pressure in plant leaves.

Section “Promotion of Measures for Water Conservation”. This provides information and recommendations on measures that effectively contribute to water conservation. The section provides information on soil cultivation measures both before sowing and during the vegetation of plants, which contribute to reducing water infiltration into the deep layers of the soil.

Information is also provided on measures that contribute to reducing the evaporation of moisture from the soil surface. As such, measures are presented for tillage (inter-row cultivation of the soil) and the use of various materials to cover the soil surface (mulch) and measures to reduce the wind force over the surface of the irrigated field (use of forest strips). Section “Calculator”. In this section, users who want to install water-saving irrigation technologies at their irrigated fields, in particular, a drip irrigation system, can determine the approximate cost of purchasing and installation of drip irrigation system.

The calculator takes into account various types of crops and various options for planting schemes. At the same time, in drip irrigation systems for orchards and gardens, irrigation hoses with special drippers are suggested, for field drip irrigation systems that are designed to irrigate field crops with a wide-row planting pattern, irrigation hoses with ordinar droppers are used.

Knowledge about the price of drip irrigation systems allows farmers to make decisions on attracting investments for introducing drip irrigation systems and successfully conclude contracts for the installation of drip irrigation systems. The section of the mobile application “Useful Links” provides information about the legal framework (legislative acts) useful for farmers' water management. This section also presents various newsletters, recommendations and guidelines promoting the rational use of water resources.

The latest version of the mobile application also presents the “News” section, which publishes various interesting information and stories about effective methods of using water resources. This section is updated daily with new information from around the world.

Thus, the use of various information and communication technologies in the field of water use such as the Tomchi mobile application improved the awareness of water consumers about water-saving irrigation methods and, along with government measures to stimulate the use of water-saving technologies, contributed to an increase in the efficiency of water use in agriculture. At the same time, the area of irrigated land in Uzbekistan, where water-saving irrigation technologies are used, has increased about 5 times over the past 3 years, and the volume of water resources used has been reduced by 20% throughout the country.

Telegram group is one of the main channels for direct communication with the large audience of farmers and WST producers. The number of subscribers of the "Tomchi” channel coupled with the group “Tomchi experts" is steadily growing, though the audience, as well as the thematic area, is very specific 7 to 10 posts are published daily totaling to around 3000 per year. Most of the articles are prepared as a response to the requested questions asked in the group. Having understood that TOMCHI expert group is the place for getting answer to any urgent question, the number of subscribers radically increase from 2170 at the end of 2020 approaching to 4500 in December of 2021.

The number of videos in TOMCHI YouTube channel is steadily growing due to project's own videos created and videos related to the topic collected by the project staff. The number of videos has grown significantly after collaboration with the water saving technology producers was established. The country's largest producers contact the project requesting to place the videos with their projects on installing WST in various regions for various crops, making the channel one of the main video platforms for knowledge sharing and promotion of WST. The videos are also uploaded on national video Streaming platform mover.uz, which is free of change.

CREATION CONDITIONS FOR INNOVATIONS IN THE ZONE OF THE ARAL SEA CRISIS

Vadim Sokolov[1]

Extended Abstract

On May 18, 2021, the UN General Assembly adopted a special Resolution 75/278 "Declaring the Aral Sea region a zone of environmental innovations and technologies". The concept of such zone is effective mechanism for implementation of the principal post-2015 intergovernmental agreements which Uzbekistan signed with responsibility – namely: 2030 Agenda and Sustainable Development Goals, Paris Agreement on Climate Change, and Sendai Framework on Disaster Risk Reduction 2015-2030 - for the Aral Sea Basin.

We are fundamentally changing the ideology of solving the Aral catastrophe: we do not just draw attention to the ecological crisis in order to reduce its negative consequences, but create a mechanism to eliminate it. The Concept coverage area is the whole Central Asia, taking into account common regional approach to implementing measures in the Aral Sea basin, with priority results aimed to improving socio-economic and environmental situation in the Priaralye. There is need for fundamental change in practice and scope, which can lead to restoration and functional integrity of ecosystems which are the basis for socio-economic development in the Aral Sea region. Strategic priorities for development of innovations in the Aral Sea region:

- creation of legal and regulatory framework
- creation of financial system for attraction innovations
- creation of scientific platform for the Aral Sea region
- growing qualified personnel and support networking among research institutions and universities, stimulation of creativity

The regulatory framework should provide mechanisms and instruments for regulating relations at the regional level, taking into account the rules and norms of international law, aimed at improving effectiveness of the water resources management system in the Amudarya and Syrdarya river basins, including incentives and responsibility mechanisms, as well as water resources management rules, guaranteeing conservation of water resources and electricity, ensuring a guaranteed water supply for the Aral Sea it-self.

Keywords: Aral Sea, Ecological innovations, Ecosystems restoration, Socio-economic developments, Environmental crisis stabilization

Crisis of the Aral Sea

The Aral Sea, which was unique, beautiful and one of the largest inland water bodies in the world, almost ended up on the verge of a complete extinction, spelling unprecedented disaster and irreparable damage to the life of the more than 60 million people living here, to the ecosystem and biodiversity of the Aral Sea and adjacent territories. The Aral Sea with its significant water surface (over 69.790 km^2) and water volume about 1080 km^3, served until the mid-1960s as a climate control reservoir and mitigated sharp weather fluctuations in the Central Asian region. Coming to the region, mainly from the west, the air masses warmed up in the winter, and cooled in the summer over the water area of the Aral Sea. Due to this temperature regime, the moisture, carried by air currents, fell out as precipitation over the mountains of Tien Shan and Pamir in the autumn-winter period, replenishing snow cover and volume of the glaciers.

Since 1960, in connection with the intensive irrigation and hydropower development in the Aral Sea basin, the total water consumption in the Amudarya and Syrdarya basins began to increase rapidly due to regulation and irretrievable withdrawal of surface runoff: 7.7 km^3 / year in 1961-1965; 17km^3 / year in 1966-1970; 30km^3 / year in 1971-1975 and up to 50 km^3 / year or more at the end of the 80s. Thus, since 1960, the negative water balance of the sea has become the norm and, from 1970 to 1990, the annual balance deficit exceeded 30 km^3.

The formation of such big deficit in the sea balance is also largely due to climatological factors - in the seventies the water formation in the Amudarya and Syrdarya rivers was 20-25% lower than normal and the total renewable water resources of the Aral Sea were 20-25 km^3 / year less than before.

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Figure 1. The Aral Sea Basin - relevant territories of Afghanistan, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan

Table 1. Water Balance of the Aral Sea, km^3/year

Time period	Water income		Losses for Evaporation	Balance
	Rivers flow	Precipitation		
1911-1960	56,0	9,1	66,1	-1,0
1961-1970	43,3	8,0	65,4	-14,1
1970-1980	16,7	6,3	55,2	-32,2
1981-1990	3,9	6,2	43,7	-33,6
1991-1994	21,0	4,6	33,6	-8,0
1995-2002	4,81	3,5	28,6	-20,29

The Aral Sea was divided into the North and South in 1989 as a result of lowering the water level and drying out of the Berg Strait. By the end of the 1990s, the Great (Southern) Aral Sea turned into a hyperhaline (salt) reservoir. Salinity in 1997 was 57‰ (ppm). In 1997, Barsakelmes island was connected to land, in 2001 - Vozrojdenie island.

In 2003, the South Aral Sea was divided into eastern and western parts, which were connected by a narrow strait Uzun-Aral, located at an altitude of 29 m. This location does not allow the mixing of water from two reservoirs. In 2004, the small lake Tuschibas, which was previously the eponymous Gulf of the Aral Sea, was separated from the Eastern part. In 2005, the Small Aral Sea was cut off from the Great Sea by the Kokaral dam - in Kazakhstan. Both water bodies were finally disconnected.

The Kokaral dam, which blocks the Berg Strait in between the North Aral Sea (Small Sea) and the South Aral Sea (Big Sea), was designed to regulate the water level in the Small Sea. The length of the dam is 13,034 m, the width is up to 100-150 m. The height of the dam crest is 6 m (45.5 m abs), the filling of the Small Sea is supposed to reach 42.2 m abs. A structure with nine spillways to discharge of 600 m³ / s was built on the dam to release excess water.

Today, the surface area of the remaining parts of the Aral Sea is less than 10% of the area in 1960. It is distributed between three reservoirs - the Western Sea with an area of 3.12 thousand km^2, the Eastern Sea with an area of 0.50 thousand km^2, and the Small (Northern) Aral - with an area of 2.35 thousand km^2. Accordingly, the volume of water decreased by almost 15 times.

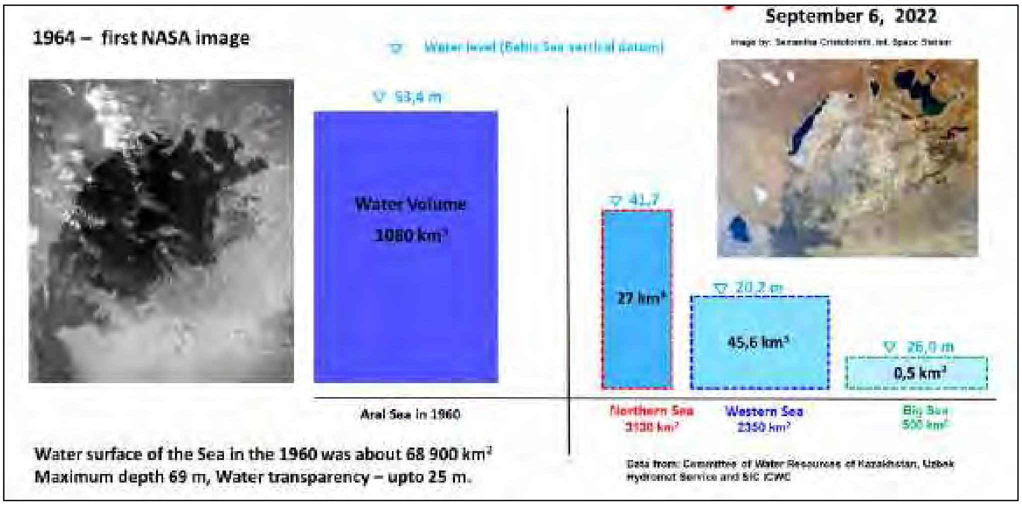

Figure 2. The Aral Sea in the Past and Today

For the full restoration of the Aral Sea, 1080 km^3 of water (sea volume at the level of 1950s) plus about 50 km^3 annually will be required to compensate evaporation losses. The total annual runoff of the Amudarya and Syrdarya rivers is about 120 km^3. Thus, in order to fill the sea in the same volume, it will be necessary to completely stop all economic activity in the basin for at least 30-40 years - that is mostly unrealistic!

Summit of Heads of States of IFAS founders

Due to active work of the International Fund for Saving the Aral Sea, in 2018, two meetings of the Fund's Board were held and in August the IFAS Summit of the Heads of the Founding States of IFAS was held in Turkmenistan, which gave new impulses to solving the problems of the Aral Sea.

The President of the Republic of Uzbekistan, Shavkat Mirziyoyev suggested a number of important initiatives that, if they are implemented, will be able to: - "dramatically improve the unfavorable environmental situation in our region." For this “decisive and non-standard measures are needed”.

The main initiative of the President of Uzbekistan - to declare “Priaralye - the Zone of Environmental Innovations and Technology”. The Objectives of this initiative is - to create conditions for common actions taken by the countries in the Aral Sea basin aiming to transform zone of ecological crisis associated with drying of the Aral Sea into a zone of socio-economic developments through introduction of environmental innovations and technologies.

Unfortunately, until today there is no in-depth analysis of the results of the three programs (ASBP) within the framework of IFAS. However, we can prove that over the past 25 years, the provisions of the Concept to solve the problems of the Aral Sea, which was adopted by IFAS in 1993, have practically become obsolete. Much has been done by the countries to mitigate the consequences of the Aral Sea disaster, the socio-economic conditions in the regional countries have changed, the water situation in the region has changed dramatically. In the Aral Basin, as elsewhere in the world, the impacts of climate change are really observed. Many other factors also indicate that it is time to change practices regarding the creation of ecosystem resilience with economic growth.

Concept “Aral Sea Area Zone of Environmental Innovations and Technologies”

On May 18, 2021, the UN General Assembly adopted a special Resolution 75/278 “Declaring the Aral Sea region a zone of environmental innovations and technologies”.
Following this support from the UN there was adopted Resolution of the Cabinet of Ministers No. 41 of January 25, 2022 "On additional measures to turn the Aral Sea region into a zone of environmental innovations and technologies **“.** This document was developed as part of the implementation of Presidential Decree No. PP-5202 of July 29, 2021 “On measures to implement the special resolution of the United Nations General Assembly of May 18, 2021 “On declaring the Aral Sea region a zone of environmental innovation and technology.” Document approved:

- The concept of transformation of the Aral Sea region into a zone of ecological innovations and technologies;
- Multilateral "Roadmap" on the priorities of attracting foreign investment in the Aral Sea region for 2022-2026.

The concept includes the following areas:

- Creation of "driver" clusters for technological innovations, including introduction of effective methods of ecosystem management, in particular, new technologies that save natural resources;
- Development and implementation of economic and financial innovations, formation of market and price mechanisms necessary to stimulate technological innovation and create "green" jobs;
- Implementation of innovative policies and legal innovations, including reducing risks associated with climate change, implementing agricultural and green economic strategies, and implementing land reforms that stimulate investment by landowners.

The multilateral "road map" for attracting foreign investment in the Aral Sea region for 2022-2026 includes:

- Priorities for implementation of measures for integrated development of the Aral Sea region in 2022-2026;
- Measures to expand international cooperation for sustainable development of the Aral Sea region and monitoring of programs and projects implementation;
- List of projects aimed at sustainable development of the Aral Sea region.

Coverage area for activities is the whole Central Asia (five countries – Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan plus Afghanistan in coming future), taking into account common regional approach to implementing measures in the Aral Sea basin, with priority results aimed to improving socio-economic and environmental situation in the Aral Sea zone. We are suggesting fundamental change in practice and scope of policy developments and implementing actions, which can lead to restoration and functional integrity of the ecosystems which are the basis for socio-economic development.

The concept “Aral Sea Area Zone of Environmental Innovations and Technologies” is effective mechanism for implementation of the principal post-2015 intergovernmental agreements which Uzbekistan signed with responsibility – namely: 2030 Agenda and Sustainable Development Goals, Paris Agreement on Climate Change, and Sendai Framework on Disaster Risk Reduction 2015-2030 - for the Aral Sea Basin. Common actions will be identified that simultaneously support achievement of the goals and targets of above-listed agreements. This creates opportunity to build regional and national policy coherence and foster risk-informed policy and decision-making.

Both key areas of the Aral Sea (the Small Sea in the North – in territory of Kazakhstan, and the South Aral Sea with adjacent dried bottom and remnants of the Aral Sea in Uzbekistan) lack the necessary volume of water resources due to both water balance issues (e.g. inefficient use of water and unproductive water loss) as well as the current level of water demand, which could be more efficiently managed. Uncertain (not stable in time and volume) water supply creates significant challenges to fully implement all necessary measures for ecosystem restoration and socio-economic development of the entire Aral Sea region. In principle, both the demand and supply side of water resources balance need to be supported by robust and timely data and analytics, climate risk analysis, and holistically and efficiently managed. By implementing proposed Concept - on income side of water balance - water management system (such as unproductive water loss reduction) will be improved, ensuring a predictable and stable flow of water to the Amudarya and Syrdarya river deltas, based on regional cooperation of all countries of the Aral Sea basin in water conservation, management and optimal use of transboundary water resources. On out-come side of water balance, agreed measures will be implemented to reduce the consumption and ensure proper balance between supply and demand.

Along with the Road-mapt, a multi-stakeholder (private-public/governmental) partnership will be nurtured through establishment of an Aral Sea Region Innovation Platform, to roll out a deep demonstration of rapid, systemic change, building on key processes and policies already underway, but without mistakes from the past. Proposed innovation approach is that in complex and uncertain contexts answers are not possible through analysis alone, the situation can be changed by experimentation.

Our innovation approach has emerged from recognition that complexity of environmental, social and economic problems as faced in Karakalpakstan (Uzbekistan) and Kyzylorda (Kazakhstan) cannot be addressed using a traditional, linear, planning and implementation approach – the sequence of analysing-planning-implementing-evaluating does not work in complex systems contexts with existing challenges. It is the relationships and interdependencies between complex programmes, rather than implementation of individual as before. It is the coherence and scalability of systemic portfolio approach to innovation that offers a new proposition for donors, governments and private investors – an opportunity to invest in joined up, accelerated learning (in an innovation portfolio) about the optimized combination of projects that will create fastest pathway from the Aral Sea as region of crisis to region of opportunity and risk-informed sustainable development.

The overall goal of Government’s initiative is to position Uzbekistan and the Aral Sea region as a global pioneer in harnessing systems innovation to finance the transformation of the economy and society within the zone of ecological crisis, creating new and better opportunities for its people, while helping revive a declining ecosystem that should be improved and sustained over time. As a result, the well-being and prosperity of all Aral Sea region communities will be advanced and climate and ecological crisis impacts significantly reduced to support the achievement of the 2030 agenda targets.

The Program for Rational Use of Water Resources

How much water is needed to sustain remains of the Aral and water bodies and wetlands in the South Aral Sea region (including the Amudarya delta)? Those water bodies can be divided into 3 zones according to their water sources regime (Figure 3, Table 2):

1. Left-bank zone (West) - the territory under the command of the Raushan canal system, drainage collectors of KKS and GK. The main water bodies are the Sudoche wetland lakes - Akushpa, Tayly, Bolshoy Sudoche and Begdulla-Aydin, Lake Karateren and the lakes of the Karadzhar system - Mashankol, Khojakol, Ilmenkol

2. The central zone - the territory under command of the main channel of the Amudarya, canals Taldyk (Kungrad-Moynaq), Moynaq (Glavmyaso) and Marinkinuzyak. The main water bodies are the Mezhdurechinsk reservoir (including Maypost and Domalak lakes), Rybachie and Moynaq lakes, Zakirkol lake and Makpalkol lake.

3. Right-bank zone (East) - the territory under the command area by channel of Kazakhdarya, drainage collectors KS-1, KS-3. The main water body is Zholdyrbas. Also, the territory supplied by the drainage collector KS-4 to small lakes of the Akpetki gorge.

To solve problems of water supply to this zone, Uzbekistan Government initiated in 2002 project «Creation of Small Local Water Bodies in the Amudarya Delta». In result of the project by 2025, the necessary engineering infrastructure will be created, which will be able to provide the optimal water horizon for the stability of ecosystems and economic activity in the reservoirs of the southern Aral Sea region.

Table 2. Water bodies and wetlands in the Southern Aral Sea landscape

Name of water body	Water level (Baltic system), m	Area, km2	Water volume, million.m3
Dried Aral Sea area and surrounding Ustyurt Plateau			
Sarykamysh Lake and surrounding Ustyurt Plateau (shared with Turkmenistan)	8,0	959,7	70000
West Aral and surrounding Ustyurt Plateau (shared with Kazakhstan)	24,6	5110 (including water surface 3175)	43600
Left-bank (Eastern) zone of the Prearalie			
Wetland of the Sudoche lake	52,5	464,7	884
Mashankul and Khojakul Lake complex	53,0	50,7	440
Central zone (Amudarya delta)			
Mezhdurechensk water reservoir	57,0	320	420
Rybachie reservoir	51,0	64,0	136
Moynaq reservoir	51,6	97,4	163
Makpalkol lake	53,0	12,0	63,0
Maypost lake	55,0	27,1	30,0
Zakirkol lake	56,5	15,8	17,8
Right-bank (Western) zone of the Prearalie			
Zholdyrbas Lake	52,0	297,2	477
Akpetki Lakes and surrounding	53,0	391,5	100
Sub-total in Prearalie		**1740,4**	**2730,8**

Figure 3. The water bodies and wetlands in the South Aral Sea region

Important to note, that in 1995 Uzbekistan joined the United Nations Convention to Combat Desertification (UNCCD), which put certain obligations in 2016 to provide Neutral Land Degradation (NLD) - or “a condition in which the volume and quality of land resources necessary to maintain ecosystem functions and services and enhance food security remain stable or increase within a given time and space framework.”

However, the above-mentioned water stability and Neutral Land Degradation can be provided only under the condition of stable water supply to this zone through the Amudarya river and collectors. The average volume of required water supply is estimated not less than 6,0 km^3 per year. The following actions are undertaken by Uzbekistan to achieve this goal:

- Establishing coordinated with other countries water limits in the middle- and upper-stream of the Amudarya and Syrdarya basins with the determination of the degree of water availability in comparison with the actual water demand;
- Preservation of and sustainable management of wetland ecosystems and coastal corridors of the Aral Sea basin to support sustainable livelihoods, including protection of existing water bodies and improving their connectedness to increase functional integrity and a gradual ecosystem regeneration;
- Provide reduced water consumption rates in the upper- and lower-reaches, by increasing their uniform water supply during the growing season and reducing all types of losses (increasing system efficiency and irrigation equipment efficiency), as well as releasing 3-4 km^3 of water along main channel of the Amudarya river for the delta;
- Transfer of part of waste (collector-drainage) waters from the Khorezm and Bukhara oasises to the lower reaches of the Amudarya - 3 km^3.

During the already mentioned Summit of the Heads of the Founding States of International Fund for the Aral Sea Saving (IFAS), which was held in August 2018, President of Uzbekistan suggested one more special initiative - “It is necessary to drastically increase the level of regional cooperation in water conservation, management and rational use of transboundary water resources”.

In response to this, Ministry of Water Resources of Uzbekistan prepared “The Water Sector Development Concept of Uzbekistan for the period of 2020-2030”. This document is recently under public discussion via Governmental web-portal and expected in August 2020 there will be released a special Presidential decree on its official adoption and implementation.

The goal of water sector development in Uzbekistan is to create conditions for meeting the ever-growing needs of people, economy and environment for water, ensure efficient water resources management and use, ameliorative condition of irrigated lands, and achieve water and food security in the context of the growing water scarcity and global climate change.

To improve efficiency of the water sector and to introduce market principles and commercial practices, proper improvements in water management system are envisaged. First, is partial transfer of water management functions to water consumers (farmer associations, WCAs, clusters, etc.) according to well-defined criteria and guidelines encompassing clear split of responsibilities, economic efficiency, social equity and environmental sustainability. Second, wider introduction of public-private partnership (PPP) and other outsourcing principles into water management system. The PPP principles suppose long-term contractual partnerships between public water utilities and private sector aimed at implementation and financing of water infrastructure projects that are currently managed by public sector and financed by the state budget. It is planned to transfer to outsourcing (with a possibility of transferring the existing utilities to trust and other forms of property management):

- Operation and maintenance of water assets;
- Rehabilitation, construction and modernization of water assets;
- Other water sector related services.

The transfer of assets and services to public and private partnership should be carried out exclusively on a competitive basis under transparent procedures. Decentralization of water system management, including outsourcing and PPP mechanisms, has the potential to increase water efficiency through water delivery cost reduction, increased water productivity and use, which will be achieved through optimization of production processes, implementation of modern technologies and creating incentives for efficient water use.

An important tool for water policy implementation is the water tax for efficient water use and penalties for water pollution and overuse. Improvement of taxation and penalty system will contribute to more efficient water use and improved water quality. In this regard, it is planned to improve a methodology for calculating tax and fine rates for different categories of water consumers taking into account their industry and technological specifics and the quality of return flow, including water salinity and other contaminants. For further wide application of water-saving technologies and increased water productivity and water use efficiency in agriculture, the following measures are expected:

- Further development of state support system for agricultural producers, who apply water-saving methods and technologies;
- Widespread implementation of water-saving technologies with water delivery using pumping stations and pumping units, including in the cultivated areas irrigated with irrigation wells and vertical drainage wells;
- Improvement of incentive mechanisms for research and development on using water-saving methods and technologies, taking into account soil, climatic and other regional characteristics of the country and incorporating lessons from past, including developing highly efficient systems that require lower maintenance costs;
- Improvement of cooperation between industrial sectors in manufacture of components and spare parts for water-saving irrigation systems, including drip and sprinkler irrigation technologies;
- Awareness raising about water saving technologies including highly efficient surface irrigation methods;
- Development of guidelines for the design, implementation and application of water-saving technologies, as well as criteria for evaluating their performance based on specifics of irrigated areas, crops and varieties;
- Organization of training, retraining and advanced training of experts on implementation and use of water-saving irrigation practices and technologies;
- Expanding the technology for crop pattern development using automated laser planners, as well as an underground closed irrigation system using modern flexible pipes;
- Development and implementation of evidence-based water rotation standards in industry and municipal services;
- Use of remote sensing systems for monitoring and targeted water productivity improvement;
- Implementation of water rotation and other arrangements, as well as technologies to control field level water losses and non-revenue water.

The main targets and indicators expected in result implementation of the Concept are as following (Table 3).

Table 3. The main targets and indicators of the Concept of water sector development in the Republic of Uzbekistan for 2020-2030

Indicator	Unit	Actual (2019)	Indicators to be achieved by years			
			2020	2021	2025	2030
Rational Use of Water Resources						
Improving efficiency rate of irrigation networks	%	0,63	0,64	0,65	0,68	0,73
Reduced proportion of irrigated areas with limited water availability	Thousand hectares	560	526	492	356	190
	%	13	12	11	8	4
Modernization of primary and inter-farm canals and increased share of canals with lining	km	9 675,7	9 960,3	10 529,4	11 425,7	13 175,7
	%	34	35	36	40	46
Replacement of existing pumping station units with energy-saving pumping units	units	732	163	163	653	1 750
Replacement of obsolete electric motors of pumping stations with new electric motors	units	1 627	214	219	903	2 100
Energy savings at pumping stations	Billion kWh	8,0	7,6	7,3	7,0	6,0
Scaling up Utilization of Water-Efficient Technologies						
Implementation of water-saving irrigation technologies	Thousand hectares	127,5	250	350	1 000	2 000
	%	3	5	8	23	47
Increased share of areas with drip irrigation technologies implemented	Thousand hectares	77,4	125	200	250	500
Improvement of Ameliorative Condition of Irrigated Lands						
Reduced proportion of salinized irrigated areas	Thousand hectares	1 935	1 926	1 906	1 852	1 722
	%	45,7	45	44,6	43	40
Reduced proportion of areas with critical level of subsurface water (0-2 m)	Thousand hectares	1 051,1	988,1	945,2	859,2	773,36
	%	24	23	22	20	18
Reduced proportion of areas with strong and medium salinity in relation to total irrigated areas	Thousand hectares	607	581	559	516	430
	%	14	13,5	13	12	10
Reclamation of land plots where cultivation was stopped	Thousand hectares	48	58,2	41,5	150,8	

Concluding remarks

The operationalization of the Concept will lead to transformational and sustained improvement in quality of lives and livelihoods of people in the Aral Sea region and restoration of a vibrant ecosystem and increased biodiversity of the Aral Sea basin.
Theory of change of the Concept is to develop a coherent, flexible Aral Sea Region Innovation Platform, adopting innovation approach to empower diverse groups of people to change practice, through exploration, experimentation and deep demonstrations. Initially in Karakalpakstan and then engaging the wider Aral Sea region, building on the Human Security Principles.

Our collective efforts in the Aral Sea region can be an inspiration for transformative, systems innovation approaches in other complex crisis regions across the world.

DECISION SUPPORT IN SUBSURFACE DRIP IRRIGATION SYSTEMS DESIGN IN THE CONTEXT OF IRRIGATION RESTORATION IN UKRAINE

Prof. Romashchenko Mykhailo[1], Dr. Bohaienko Vsevolod[2], Mrs. Sardak Anastasiia[3]

ABSTRACT

"Irrigation and Drainage Strategy of Ukraine up to 2030" provides for irrigated area increase by 1.0-1.2 mln ha. Irrigation potential raise is possible ensuring efficient water usage given strong manifestation of climate change in Ukraine and infrastructure destruction due to Russian aggression. Efficiency is achieved applying water-saving irrigation methods and decision support systems during their design and operation.Among such methods, subsurface drip irrigation systems requires significant costs for construction and operation. We propose a technique for the determination of its design parameters (installation depth and distance between pipelines) based on the modelling of moisture transport.

We use two-dimensional Richards equation in terms of pressure with parameters – water retention curves and hydraulic conductivity - determined processing laboratory analysis results.Irrigation is simulated maintaining average moisture content in the root zone in a narrow range of high values (>80% of field capacity (FC)). Another considered option is pulse irrigation with maintainable range of 90-95% - 100% FC in the root zone's part located close to emitters. Determining the irrigation regime that ensures optimal water consumption with minimal infiltration water losses is performed using mathematical modelling.

System's resilience to weather extremes and climate change is assessed simulating meteorological scenarios series generated by a stochastic weather generator. The objective function is the costs for system creation and operation averaged over all meteorological scenarios. Its minimization is performed by a genetic algorithm.Since modelling the entire growing season is a computationally complex problem, we consider only the period of maximum water consumption.

Computational experiments' results demonstrates compliance with the practice of designing subsurface drip irrigation in southern Ukraine. Further technique's development is possible applying it for the generation of practical recommendations for various crops and climatic zones.

Keywords: subsurface drip irrigation; moisture transport; modelling; optimization

1. Introduction

One of the most important problems of humanity, namely the food problem, is not solved with the passage of time but, on the contrary, worsens. Climate change and population growth are the main drivers of this aggravation. One of the ways to solve this problem is the development of irrigation as a tool to ensure sustainability and higher productivity of agriculture in the conditions of progressive climate change. Ukraine belongs to the number of countries that, according to the definition of FAO, have a leading role in solving the world food problem. Its agricultural resource potential, provided that modern farming technologies are used, is sufficient for food production in volumes sufficient to feed at least 500 million people.

The realization of these opportunities is limited by insufficient level of natural moisture supply on the one hand and the military aggression of Russian Federation on the other. Regarding the latter it is possible to suggest that this action is temporary and with the joint efforts of the people of Ukraine and international community, the aggression of Russian Federation against Ukraine will be stopped and Ukraine will be able to take measures to restore full-fledged economic activity throughout its territory within the internationally recognized borders, including the agricultural sector of economy, the role of which, as already noted, is extremely important for solving the world food problem. The only factor, which will affect sustainability and efficiency of agriculture, will remain insufficient level of natural moisture supply that will continue to deteriorate due to climate change. Indeed, according to forecast data (Romashchenko et al., 2020) from 65% (in 2050) to 80% (in 2100) of the territory of Ukraine will be characterized by a significant (over 150 mm) deficit of climatic water balance (Fig. 1).

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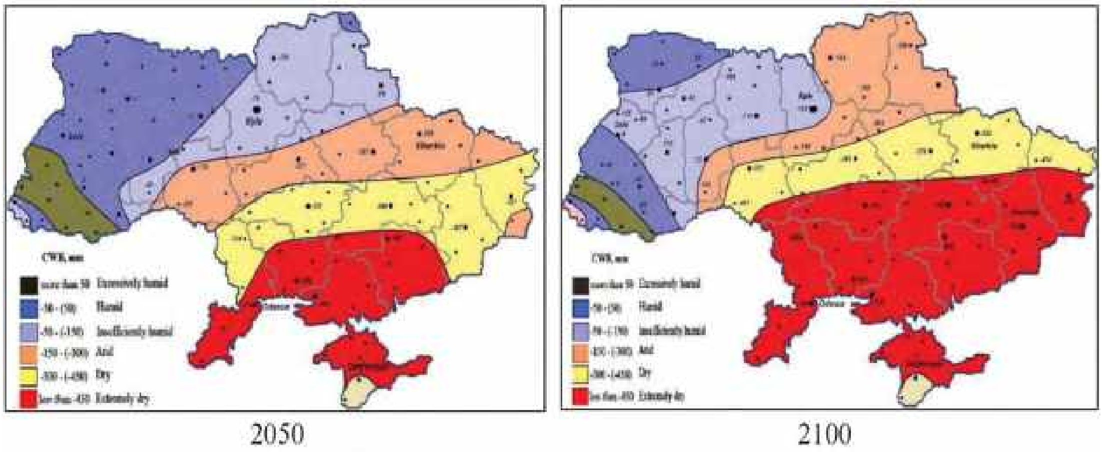

Figure 1. Forecast of moisture supply conditions in Ukraine according to annual climatic water balance
*source: Romashchenko et al. (2020)

Under these conditions, sustainable agriculture without irrigation will be impossible. That is why the Cabinet of Ministers of Ukraine approved the "Irrigation and Drainage Strategy in Ukraine for the period until 2030" and the Action Plan for its implementation developed with the participation of experts from the World Bank and FAO. These government program documents provide for an increase in irrigated areas by 1.0-1.2 million hectares, as well as water regulation using drainage systems on ~1.0 million hectares. Therefore, taking into account the significant increase in the water demand of agricultural crops to cover the deficit of natural water supply, the main methods of irrigation that will be used are low-pressure and low-intensity sprinkling irrigation along with drip irrigation. Moreover, the volumes of drip irrigation's application due to significant, compared to sprinkling irrigation, saving of water, fertilizers, and electricity will constantly grow. But the process of the extension of drip irrigation's application, especially the most prospective of its varieties — the subsurface drip irrigation — needs the solution of several technical and technological problems. These problems are related to the substantiation of the parameters of subsurface drip irrigation systems (SDIS) with respect to the conditions of their application and water supply regimes, the usage of which allows obtaining maximal economic effect with minimal capital expenses on their construction and the expenses of irrigation water on the unit of crop yield.

The design parameters of SDIS, which need to be determined, include the depth of installation and the distance between irrigation pipelines. The importance of the correct definition of these parameters is due to their decisive influence both on the amount of capital expenses for the construction of SDIS and on the possibility of forming a favourable soil water regime for the development of irrigated crops with minimal water consumption.

According to the data of experimental studies, the consumption of irrigation water depends not only on the structural parameters of SDIS, but also on the water supply regime. Therefore, in addition to the determination of installation depth and the distance between irrigation pipelines, the research problem also includes the substantiation of water supply regime for subsurface drip irrigation.

Determining the design values of SDIS parameters can be carried out using expert assessments or mathematical modelling tools. The basis of such modelling is, on the one hand, a description of moisture transport processes in soils, and on the other hand, a technological approach to the determination of irrigation schedules and rates on the base of plant development models. The main approach to the scheduling of irrigation is based on monitoring moisture supply to the root layer of soil (Campbell et al., 1982; Sharma et al., 2021).

Models of moisture transport under drip irrigation (Arbat et al., 2008; Romashchenko et al., 2016) are based mainly on Richards differential equation (Richards, 1931) in two-dimensional setting or are constructed from experimentally determined contours of moistening (Holzapfel et al., 1990). Algorithms for automating the selection of parameters of subsurface drip irrigation systems can be considered as an optimization procedures superposed on moisture transport models with objective functions based mainly on the economic evaluation of efficiency and limitations arising from the biological need to provide plants with moisture.

Among the works studying algorithms of this class, we can highlight Kandelous et al. (2012), Seidel et al. (2015), and abd el Baki et al. (2017).

The pulse regime of water supply for drip irrigation (Rank and Vishnu, 2021; Karmeli and Peri, 1974) provides, in contrast to constant irrigation, the supply of water to the zones of maximum concentration of plants' root systems in the shortest possible cycles of fixed or variable duration in accordance with the actual water demand. The use of the pulse irrigation regime makes it possible to create moisture levels higher than field capacity (FC) in certain zones of the moistened volume. In this way, moisture and nutrients become more available to plants in the respective zones than in the cases when other irrigation regimes are used. This, in turn, leads to more intensive growth of plants' root systems in the moistened zones (Segal et al., 2006; Shani, 1991), which is one of the main features of the pulse regime of drip irrigation.

Differential models of moisture transport allow without significant corrections to carry out predictive modelling when irrigation regimes, soil, or crop parameters are changing. At the same time, from the best of our knowledge, most of the studies on such modelling and its use in decision support in irrigation (see, e.g. Friedman et al. (2016), Gonzalez Perea et al. (2020), Phogat et al. (2012)) consider fixed root systems of plants without taking into account the hypothesis regarding their dependency on the moistened zone during the pulse drip irrigation.

2. Modelling tools

Richards equation (Richards, 1931) stated in terms of water head in two-dimensional setting has the form (Romashchenko et al., 2021)

$$C(h)\frac{\partial H}{\partial t}=\frac{\partial}{\partial x}(k(H)\frac{\partial H}{\partial x})+\frac{\partial}{\partial z}(k(H)\frac{\partial H}{\partial z})-S, 0\le x\le L_x, 0\le z\le L_z, t\ge 0 \quad (1)$$

where $h(x,z,t)=\frac{P(x,z,t)}{\rho g}$ is the water head, *m*, $H(x,z,t)=\frac{P(x,z,t)}{\rho g}+z$ is the full moisture potential, *m*, $P(x,z,t)$ is the suction pressure, *Pa*, ρ is the density of water, *kg/m³*, g is the acceleration of gravity, *m/s²*, $C(h)=\frac{\partial\theta}{\partial h}$ is the differential soil moisture content, *%/m*, $\theta(x,z,t)$ is the volumetric soil moisture content, *%*, $k(H)$ is the hydraulic conductivity, *m/s*, $S(x,z,t)$ is the source function, *%/s*, that simulates the extraction of moisture by plants' roots and its supply by subsurface drip irrigation.

The model based on equation (1) in two-dimensional setting assumes that the distance between emitters is sufficient for the formation of a uniform moistened zone along irrigation pipelines.

Boundary and initial conditions subject to Equation (1) as well as the form of source function are given in Romashchenko et al. (2021). We assume that a fixed number of plants and a given number of irrigation pipelines are placed at a given depth in the solution domain.

Water retention curves of soils are described by van Genuchten's model (van Genuchten, 1980) in the form $\theta(h)=\theta_0+\frac{\theta_1-\theta_0}{\left[1+\left(10\alpha|h|\right)^n\right]^{1-1/n}}$ with coefficient values that vary from layer to layer and can be obtained fitting the model to laboratory studies' results. The dependency between hydraulic conductivity and pressure is represented according to Averyanov's model (Averyanov, 1982) in the form $k(H)=k_f\left(\frac{\theta(H-z)-\theta_0}{\theta_1-\theta_0}\right)^{\beta}$ where k_f is the saturated hydraulic conductivity, β is the fixed exponent, the values of which are taken from experimentally obtained dependencies $k(H)$.

The appointment of watering is modelled at the time when average moisture content in the root layer of soil becomes less than a specified value. Watering continues until the value of this indicator reaches 100% of FC.

Numerical solution of the initial-boundary value problem for the model based on Equation (1) is performed according to the implicit finite-difference Crank-Nicolson scheme (Samarskii, 2001) on a uniform grid. Systems of linear algebraic equations are solved by the TFQMR algorithm (Freund, 1993). The starting time step was taken equal to 1 s with its further change during the calculations in order to achieve optimal balance of accuracy and speed.

Meteorological scenarios are generated by a stochastic weather generator (*weathergen* software was used - https://github.com/ARVE-Research/gwgen). The Hargreaves-Samani formula (Hargreaves and Samani, 1985) is used to obtain estimates of potential evapotranspiration. This approach allows, in particular, to carry out simulations taking into account climate change adjusting the input climatic data based on the scenarios of predicted changes.

The depth of root system together with the values of Leaf Area Index (LAI) and crop coefficient in the proposed simulation technique are determined based on the model of changes in crop's development stages with the accumulation of a certain amount of average daily temperatures (Rithchie and Nesmith, 1991). It is assumed that the corresponding parameters vary linearly from stage to stage. The date of crop sawing is set as an input parameter of the model, after which the duration of the growing season and the dynamics of LAI, root system's depth, and crop coefficient are determined based on the generated meteorological scenario.

The proposed algorithm for optimizing structural parameters of subsurface drip irrigation systems has the following peculiarities:

1) A given number of randomly generated meteorological scenarios is considered;

2) The objective function to be minimized is the sum of the expenses for the creation of the system and for the supply of water during a given period under unchanged crop and its growing conditions averaged over all weather scenarios.

3) Minimization of the objective function is performed by a genetic algorithm (Mitchell, 1996).

Since modelling the entire growing season under several weather scenarios is a computationally complex task, a simplified model is proposed based on the assumption that subsurface drip irrigation systems are able to provide adequate moisture throughout the season if they are able to do so during the period of maximum water consumption.

When modelling the pulse regime of subsurface drip irrigation we proceed from the hypothesis that root system is developing in the zones moistened by emitters and its size depends on the size of these zones (Segal et al., 2006; Shani, 1991). The size of the root-containing zone is determined by the method of successive approximations depending on the moistened zone created by the watering at a given rate.

The duration of watering when simulating the pulse regime is considered fixed with the schedule adapted the to changes in soil moisture, which is typical for automatic management of drip irrigation (Obaideen et al., 2022). At the same time, due to the adaptation of the root system to the irrigation regime, maintenance of a given narrow range of moisture content in the root zone is achieved.

3. Testing of modelling tools

Testing of the proposed methodology was carried out on the basis of monitoring data obtained in 2020 during the cultivation of corn in the State Enterprise "Experimental Farm “Veliki Klyny" (Kherson region, Ukraine).The procedure for optimizing the parameters of the subsurface drip irrigation system was performed for the case of modelling a range of 10 days at the highest level of water consumption (5.1 mm/day) while maintaining moisture content in the ranges of 80-95% of FC and 90-95% of FC.

In the case of a pre-irrigation threshold at the level of 80% of FC, the best option according to the simulation results was to install drip pipelines at the distance of 66 cm from each other at the depth of 21.8 cm. The calculated distance between the pipelines and the depth of their installation were close to the distances used in the experiment. The average seasonal volume of water supply among 10 random weather scenarios was equal to 701 mm (27 irrigations with a rate of 22-29 mm) with a coefficient of variation equal to 3%, seasonal evapotranspiration equal to 465 mm, and total precipitation equal to 168 mm. It can be stated that at a given level of hydraulic conductivity, the range of maintained moisture content, and the dynamics of root-containing layer's depth, significant water losses are possible due to infiltration into the layers below the root zone.

In the case of a pre-irrigation threshold equal to 90% of FC, the determined optimal values of system's parameters did not significantly differ from the case of 80% of FC: the distance between the pipelines was 62 cm with the installation depth equal to 21.5 cm. The seasonal volume of water supply was 1063 mm (124 irrigations with a rate of 13 mm). Thus, according to the simulation results, with soil's saturated hydraulic conductivity equal to 15 cm/day, an increase in the pre-irrigation threshold leads to a significant increase in water losses.

Mathematical modelling of the pulse regime was carried out using the hydro-physical characteristics of 20 types of soils of Ukraine obtained on the base of the data on their granulometric composition using *Rosetta* software. Soils were considered homogeneous, data on their upper layer (up to 20/30 cm) were used throughout the simulation domain depth. The value of the parameter β in Averyanov model was assumed to be equal to 3.5 for all 20 soils. Based on the simulation results, it can be concluded that the infiltration below the 1 m layer, which are the main cause of irrigation water losses in all simulated scenarios, are primarily correlated with the filtration coefficient (R^2=0.6) as well as with the volumetric moisture content value for field capacity (R^2=0.7).

At the same time, the modelled residual of water balance, which is defined as the accumulation or use of moisture reserves in 1 m soil layer, significantly correlates with water head value at the level of field capacity (R^2=0.86).

The total volume of irrigation shows the strongest correlation with the parameter n of van Genuchten model (R^2=0.63). However, this level of correlation is first provided by soils for which $n<1.2$. Such values in the studied dataset correspond to absolute values of water heads at the level of field capacity more than 30 kPa and the situations when higher irrigation rates than the specified basic rate of 3 m^3/ha are required to maintain moisture content in the range of 95-100% of field capacity. If we consider soils with $n>=1.2$, the total volume of irrigation has high correlation level with the same initial parameters as infiltration below 1 m layer: the filtration coefficient (R^2=0.65) and the volumetric moisture content value for field capacity (R^2=0.75).

Considering the connection of the modelling results with hydro-physical properties of soils, particularly their filtration and water-holding capacity, we can state that on soils of heavy mechanical composition (heavy loams, clays) with low filtration and high water-holding capacity the pulse regime of water supply to the moistened zones should maintain moisture level as close as possible to field capacity with relatively large irrigation rate per pulse and low frequency of pulses. On soils of light mechanical composition (sandy soils, sandy loams) with high filtration and low water-holding capacity in moistened zones it is necessary to maintain a lower level of moisture supply, but in the narrowest possible range (90-95% of field capacity) that requires conducting irrigation at lower rates with higher frequency of pulses.

4. Conclusions

The determination of cost-effective design parameters of subsurface drip irrigation systems requires combined consideration in the optimization problem of such factors as soil moisture transport, crop development, and variability of weather conditions. The proposed approach of solving this problem uses a genetic algorithm to find such a depth of irrigation pipelines installation and a distance between them that would ensure maintaining a given range of root zone moisture content with minimal expenses for system construction and operation within a given period. Consideration of a series of randomly generated weather scenarios allows assessing the impact of possible extremes in weather conditions on the ability of the system to maintain the required level of moisture content and allows taking climate change into account.

The conducted computational experiments demonstrated the correspondence of the modelling results to the observation of the dynamics of moistened zones and the general practice of designing subsurface drip irrigation systems in the conditions of southern Ukraine.

The developed technique of modelling moisture transport in the conditions of the pulse regime of water supply under drip irrigation is based on the hypothesis that in this case root systems of plants develop first in the zones of active moistening. For a given duration of watering, the technique allows evaluating irrigation water losses, the use of moisture reserves, and system's resistance to changes in water demand, providing information about the efficiency of irrigation water usage to decision-makers.

The results of the simulation of the pulse regime according to the developed technique strongly suggest that on soils with heavy mechanical composition the pulse regime should maintain a high level of moisture supply with a relatively large irrigation rate per pulse and low frequency of pulses. On soils with light mechanical composition, irrigation regime should have the opposite character — lower rates with higher frequency of pulses.

Further development of the technique is possible in the direction of its application for the generation of practical recommendations for growing different crops in different climatic zones and for the substantiation of projected water supply regimes to achieve the maximum level of economic efficiency of irrigation.

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LCOMPARING EFFECTS OF SPECIFIC POWER AND DROPLET SHEAR STRESS ON SOIL EROSION FOR LOW-PRESSURE SPRINKLERS

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ABSTRACT

Specific power or droplet shear stress is generally considered to be the most critical indicators affecting soil erosion in sprinkler irrigation, but there is controversial about which indicator has a greater impact. This brings the uncertainty to optimization design of low-pressure sprinkler irrigation systems. In this study, we took the commonly used low-pressure sprinkler, i.e. Nelson D3000 as the object, and carried out the soil box experiments to study the effects of specific power and average droplet shear stress at the end of spray jet on soil erosion of sprinkler irrigation, under three nozzle diameters (3.97, 5.95, and 7.94 mm), two operating pressures (103 and 138 kPa), and two soil textures (loamy sand and silty loam). Overall, the larger specific power or average droplet shear stress resulted in higher initial and steady runoff rates and shorter time until runoff occur and stabilize. Enlarging the specific power or average droplet shear stress could significantly increase the initial infiltration rate, sediment yield, and surface soil bulk density, but the infiltration depth prior to runoff and surface soil porosity decreased. Furthermore, the specific power was observed to have greater correlations than average droplet shear stress with the surface runoff rate, initial infiltration rate, and increase in the soil bulk density and decrease in the soil porosity after irrigation. Whereas, it was weakly related to the infiltration depth prior to runoff and sediment yield, indicating that the specific power could more accurately reflect the soil erosion with respect to the shear stress. To minimize the risk of soil erosion, it was recommended to select a small diameter nozzle (3.97 mm) and operating pressure (103 kPa) in the design of low-pressure sprinkler irrigation systems. This research can provide a technical support for optimization of sprinkler irrigation systems and soil erosion prevention.

Keywords: Soil Infiltration, Surface Runoff, Sediment Yield, Specific Power, Droplet Shear Stress, Low-Pressure Sprinkler

1. Introduction

As one of the efficient water-saving irrigation methods, sprinkler irrigation has been widely used all over the world. According to the statistics of International Commission on Irrigation and Drainage (ICID), the sprinkler irrigation area in the world has reached 3.8×10^7 ha by 2019, up to 13% of the total irrigation area (Hui et al., 2022a). Nonetheless, soil erosion often occurs during sprinkler irrigation, resulting in the losses of soil, water, and fertilizer in the farmland, which in turn pollutes the environment (Silva, 2006; De Jong et al., 2011). There are many factors affecting the soil erosion in sprinkler irrigation, including the soil type, vegetation coverage, and hydraulic performance of irrigation systems (Koluvek et al., 1993; Bjorneberg et al., 2000; Santos et al., 2003). When the field conditions keep the same, the hydraulic performance becomes the primary cause that determines the soil erosion. Among many hydraulic performance characteristics, the specific power has always been considered to be the most closely related to the occurrence of soil erosion, and is commonly used to evaluate the quality of sprinkler irrigation systems (Mohammed and Kohl, 1987; Yan et al., 2011; Al-Kayssi and Mustafa, 2016; Ge et al., 2020). However, in recent years, some researchers have observed that mechanistically, the soil erosion under sprinkler irrigation was mainly attributed to the droplet shear stress generated by the impact of a droplet on the ground, rather than the specific power (Chang and Hills, 1993a; Chang and Hills, 1993b; Hui et al., 2021a). Therefore, so far, which of these two indicators has a greater impact on soil erosion is still controversial and needs to be further determined.

As a highly automated and wide-coverage sprinkler irrigation equipment, the center pivot irrigation system has always played an important role in the field of agricultural irrigation worldwide (Ortiz et al., 2010; Yan et al., 2020; Baiamonte et al., 2021). By the end of 2019, there were more than 18,000 sets of center pivot and linear-move irrigation systems used in China, with the irrigation area of nearly 600,000 hm2 that accounted for about 14.2% of the total sprinkler irrigation area (Hui et al., 2022b). Noteworthy, the proportion of center pivot in the USA was as high as 84.7% (USDA National Agricultural Statistics Service, 2019). Soil erosion is also a key factor inhibiting the

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promotion of center pivot irrigation systems. As an important part of the irrigation system, the sprinkler has a non-negligible effect on its erosion (King and Bjorneberg, 2011). Currently, the center pivot has gradually replaced medium- and high-pressure sprinklers with low-pressure sprinklers to minimize the energy requirements of the systems, thereby contributing to the global goal of carbon peak and neutrality. The center pivot low-pressure sprinklers are commonly classified into three types, namely the fixed spray plate sprinkler (FSPS), rotating spray plate sprinkler (RSPS), and oscillating spray plate sprinkler (OSPS) (Hui et al., 2021b). The different structures and operating methods of these three sprinklers result in the significant differences in their performances. Among them, the cost of FSPS is lower than that of RSPS. However, this sprinkler type attains high instantaneous application rates and poor application uniformity (Silva, 2007; Yan et al., 2011). In contrast, RSPS has the higher energy consumption in addition to its wide spraying range and relatively uniform water distribution (Faci et al., 2001; Chen et al., 2020). While for OSPS, strong wind resistance characteristics make it highly competitive in the sprinkler marketplace (Manke et al., 2019).

To clarify the soil erosion mechanism of low-pressure sprinklers, scholars have extensively investigated its impact on the soil from the perspective of the specific power (Thompson and James, 1985; Schneider and Howell, 2000; Silva, 2006; Yan et al., 2011; King and Bjorneberg, 2012). Yan et al. (2011) took the Nelson D3000 sprinkler as the object, and investigated the influence of specific power on the soil infiltration, surface runoff and other indicators through laboratory experiments. The results showed that the runoff rate, bulk density of soil surface crust, and sediment yield were generally directly proportional to the specific power; while the initiation of runoff, infiltration rate, and infiltration depth prior to the runoff were inversely proportional to the specific power. King and Bjorneberg (2012) developed a sealing soil infiltration model that considered the transient soil seal formation on a 30 min or less time scale, which explicitly used the specific powers of low-pressure sprinklers as the driving factor for formation of a soil surface seal. Thompson and James (1985) evaluated the infiltration characteristics of a silt loam soil affected by the specific powers of low-pressure sprinklers, and found that the infiltration depth prior to runoff decreased with increasing the specific power. Meanwhile, they also provided a method for determining the irrigation depth that could be applied to the silt loam without potential for runoff, based on the relationship between the specific power and infiltration depth prior to runoff. In contrast, relatively few studies have been conducted on the effect of droplet shear stress for the low-pressure sprinkler on soil erosion. At present, the relevant researches regarding shear stress effects on the soil were mainly focused on medium- and high-pressure sprinklers. For example, Chang and Hills (1993a) used a Rainbird 20JH impact sprinkler and clarified the response mechanism of soil infiltration of the three textures to shear stresses in the different droplet impact directions. However, in terms of low-pressure sprinklers, it was still in the stage of revealing the distribution characteristics of droplet shear stresses (Hui et al., 2022c), and their impacts on soil erosion have not been evaluated. In addition, it could also be found from the above studies that previous investigations on the effects of specific power and droplet shear stress on soil erosion were conducted separately, and no comparative analysis of these two indicators was carried out under same sprinkler irrigation conditions. Therefore, it was not possible to determine which one owned a greater impact on soil erosion.

The goals of this study were to investigate the soil erosion under a low-pressure sprinkler (Nelson D3000) with larger droplet impact force. Three typical nozzle diameters (3.97, 5.95, and 7.94 mm), two common operating pressures (103 and 138 kPa), and two representative soil textures (loamy sand and silty loam) were considered in the study. The specific objectives were as follows: (1) to evaluate the effects of specific power and average droplet shear stress at the water jet end on surface runoff rate, soil infiltration rate, infiltration depth prior to runoff, sediment yield, and changes in surface soil bulk density and porosity before and after irrigation; (2) to compare the correlations of specific power and average droplet shear stress with soil physical properties, and then determine which droplet indicator had a greater influence on soil erosion; and (3) to optimize the working parameters of low-pressure sprinkler.

2. Materials and methods

2.1 Experimental setup

The impact test of droplets on the soil for low-pressure sprinklers was conducted at the Zhuozhou Experimental Station of China Agricultural University, Hebei, China. The sprinkler used in the test was the Nelson D3000 (Nelson Irrigation Corp., Walla Walla, USA) with an FSPS equipped with a 36-grooved blue plate (Fig. 1), which is one of the popular low-pressure sprinklers for center pivot irrigation systems, but it has a greater impact on the soil than other types of sprinklers (King and Bjorneberg, 2010). The sprinkler was equipped with a pressure regulator and was mounted at a height of 120 cm above the ground, to keep consistent with the installation of sprinkler on most center pivot irrigation systems. The water source of the sprinkler was taken from groundwater. During the test, the groundwater was pressurized to the inlet of sprinkler by a booster pump (TD, Nanfang Pump Industry Co., Ltd., Hangzhou, China) equipped with a frequency converter (ACS510, Asea Brown Boveri Ltd., Zurich, Switzerland). Meanwhile, the inlet pressure and flow rate of the sprinkler were monitored in real time by a pressure gauge (Asmik MIK-PX400, range 0–1 MPa, accuracy of 0.5%) and an ultrasonic flowmeter (Letrue LCF-U, range 0–330 m^3 h^{-1}, accuracy of 2%), respectively.

Figure. 1. Image of the D3000 sprinkler used in the experiment.

The droplet information of the sprinkler was obtained by a two-dimensional video disdrometer (2DVD, Joanneum Research Corp, Graz, Austria). 2DVD is the most advanced precipitation particle measurement equipment in the world and is mainly composed of three parts: measurement device, indoor user terminal, and power supply unit. This equipment can measure the size, shape, aggregation state, falling velocity and direction of a single precipitation particle (such as rain, snow, hail, etc.) in real time. It is suitable for meteorology and the environment, telecommunications and wave propagation, industrial applications and other fields (Kruger and Krajewski, 2002). In the sprinkler droplet test, the two perpendicularly disposed CCD cameras inside 2DVD continuously scanned the droplets passing through the measurement area of 100 □ 100 mm2 (Fig. 2) and recorded their water application rate, droplet diameter, and vertical and horizontal velocity components (Huang et al., 2010), thereby calculating the specific power and droplet shear stress. The minimum measuring droplet diameter of 2DVD can reach 0.19 mm.

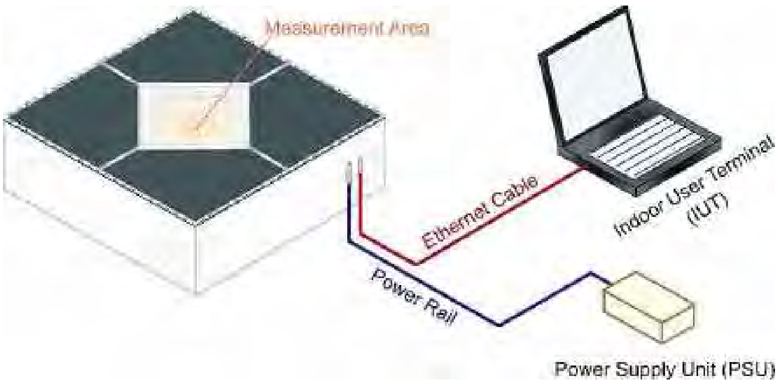

Figure. 2. Composition of the 2DVD instrument.

The soil box used in the test was made of PVC pipe bonding with an inner diameter of 15 cm and a height of 45 cm. In order to ensure the natural infiltration of soil water, four holes with a diameter of 10 mm were made in the bottom of soil box, and a thin layer of the gauze of 2-mm thickness was placed on the holes for reducing soil loss. Meanwhile, a runoff hole with 10 mm diameter was located 5 mm below the upper brim of soil box and connected with a rubber tube. The tube was conducted the runoff water into a measuring cylinder with a capacity of 250 mL. After the runoff water in the measuring cylinder was filled, it was poured into a 3 L container for the temporary storage to prevent water evaporation. Moreover, to avoid spray droplets directly entering the measuring cylinder through the upper opening, a transparent plastic cover was used. The rubber tube passed through the plastic cover through a hole bored in the center of the cover. In the experiment, an automated weather station (HOBO U30, Onset Computer Co., MA, USA) was installed within 100 m of the measuring site, collecting the meteorological data such as wind speed, wind direction, temperature, relative humidity, and solar radiation. In addition to the above experimental devices, other devices mainly included the laser particle size analyzer

(MS2000, Malvern Instruments Ltd., Worcestershire, UK), electric blast drying oven (WGL-230B, TAISITE Instruments Ltd., Tianjing, China), and ring knife (volume of 100 cm^3, Chuntu Hardware Tool Store, China), etc. for measuring soil particle composition, soil water content, and soil bulk density, respectively.

2.2 Experimental design

The impact test of droplets on the soil was carried out by the means of spraying with a single sprinkler (Fig. 3). The test time ranged from 06:00 am to 08:00 am when the solar radiation was weak. The average wind speed during this period was lower than 0.5 m s^{-1}, and the air temperature and relative humidity were around 25℃ and 70%, respectively, so the evaporation drift loss of sprinkler irrigation was almost zero. Three factors were considered in the test, they were sprinkler operating pressure, nozzle diameter, and soil texture (Table 1). Among them, the operating pressure was set to the 2 levels of 103 kPa (15 psi) and 138 kPa (20 psi), and the nozzle diameter was set to the 3 levels of 3.97 mm (#20), 5.95 mm (#30), and 7.94 mm (#40). The above operating pressures and nozzle diameters were chosen because they are commonly used for low-pressure sprinklers. In addition, the 2 typical soil textures in the North China Plain, loamy sand and silty loam, were selected. The particle size distributions of the two texture soils are shown in Table 2. Therefore, this test consisted of 12 treatments, each of which was repeated 3 times, for a total of 36 trials.

Table 1 Working parameters of the D3000 sprinkler and their corresponding locations of soil box.

Soil textures	**Operating pressure (kPa)**	**Nozzle diameter (mm)**	**Distance between soil box and sprinkler (m)**
Loamy sand	103	3.97	5
		5.95	7
		7.94	7
	138	3.97	6
		5.95	7
		7.94	8
Silty loam	103	3.97	5
		5.95	7
		7.94	7
	138	3.97	6
		5.95	7
		7.94	8

Table 2 Particle size distributions of two texture soils.

Soil textures	Percent sand (%)	Percent silt (%)	Percent clay (%)
Loamy sand	75.67	21.46	2.87
Silty loam	39.33	53.76	6.91

The soil box was arranged at the end of jet where droplets had the strongest impact on the soil (Hui et al., 2022a), in order to better compare the effects of specific power and droplet shear stress on soil erosion. The specific distances between soil box and sprinkler under different treatments are depicted in Table 1. Before the start of the test, the soil samples were air-dried and passed through a 2 mm sieve. According to the local average soil bulk density (1.40 g cm^3), the soil was evenly added into the soil box in 8 layers (depth of each soil layer was 5 cm). The interface between each of the soil layers was roughly levelled. A 2% slope was built-in by shaving the soil surface, so that the surface runoff flowed from the runoff hole at bottom of the slope. When all preparations were completed, covered the soil box with a slab and opened the valve for sprinkler irrigation. When the stable operating pressure was reached, the slab was uncovered and the timer began. In the test, the time until runoff occur was observed and recorded, and then the volume of runoff water was measured every 5 min to calculate the runoff rates under different irrigation times. The irrigation time continued until a generally steady runoff rate was obtained. After sprinkler irrigation, the surface soil with a depth of 0–20 cm was collected with the ring knife, which was used for the calculation of soil bulk density and porosity. The schematic diagram of the test is shown in Fig. 3.

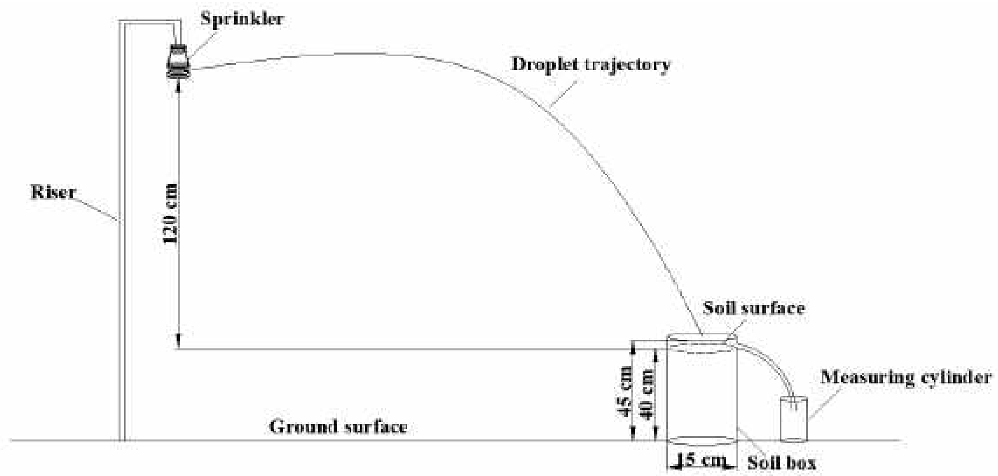

Figure. 3. Schematic diagram of the impact test of sprinkler droplets on the soil.

2.3 Calculations

(1) Surface runoff rate

The surface runoff rate was calculated from runoff water volume, soil surface area, and runoff duration by:

$$R_o = \frac{1000V_r}{A_s t_r} \tag{1}$$

where R_o is the surface runoff rate (mm h^{-1}); Vr is the runoff water volume (m^3); A_s is the opening area of soil box (m^2); and t_r is the collection time (h).

(2) Soil infiltration rate

The infiltration rate was determined by following equation:

$$I_r = P_w - R_o \tag{2}$$

where I_r is the soil infiltration rate (mm h^{-1}); and P_w is the water application rate of sprinkler (mm h^{-1}).

(3) Infiltration depth prior to runoff

The infiltration depth prior to runoff was calculated from the measured water application rate of sprinkler and time before the occurrence of runoff:

$$I_b = P_w t_b \tag{3}$$

where I_b is the infiltration depth prior to runoff (mm); and t_b is the time until runoff occur (h).

(4) Sediment yield

The runoff water collected in the container was put in the oven at a temperature of 90℃ until all water was evaporated. The temperature was then adjusted to 105℃ and the remaining samples were dried 24 h until the soil mass reached a constant value (Yan et al., 2011). The sediment yield was calculated by the following equation:

$$Y_s = \frac{M_s}{V_s} \tag{4}$$

where Y_s is the sediment yield (g mL^{-1}); M_s is the mass of sediment (g); and V_s is the total volume of runoff water collected during the test (mL).

(5) Soil bulk density

The soil samples at depth of 0–20 cm collected by the ring knife were weighed immediately, and then its soil water content was obtained by the drying method (O'Kelly, 2004), thereby calculating the soil bulk density:

$$B_s = \frac{1000G}{V_{cr}\left(100+W\right)} \tag{5}$$

where Bs is the soil bulk density (g cm^{-3}); G is the wet weight of soil in the ring knife (g); Vcr is the volume of the ring knife (cm^3); and W is the soil water content (%).

(6) Soil porosity

Soil porosity refers to the volume percentage of pores in a soil, which can be calculated by the following equation:

$$P_s = \left(1-\frac{B_s}{D_s}\right)\times 100\% \tag{6}$$

where P_s is the soil porosity (%); and D_s is the soil density (g cm^{-3}).

(7) Specific power

The specific power is closely related to the droplet diameter, velocity, and water application rate, indicating the kinetic energy of droplets per unit area and unit time at the measuring point (King and Bjorneberg, 2010). The equation of specific power is as follows:

$$S_p = \frac{P_w \sum_{i=1}^{n} d_i^3 \rho V_i^2}{7200000 \sum_{i=1}^{n} d_i^3} \tag{7}$$

where S_p is the specific power, W m^{-2}; d_i is the diameter of the *i*th droplet (m); V_i is the resultant velocity of the *i*th droplet (m s^{-1}); ρ is the mass density of the droplet (kg m^{-3}); and n is the number of droplets.

(8) Droplet shear stress

The shear stress of the droplet represents the horizontal stress generated by the droplet impacting the ground (Ghadiri and Payne, 1986), which can be expressed by the following equation:

$$S_s = 0.5\rho V_h^2 \tag{8}$$

where S_s is the shear stress of the droplet (N m^{-2}); and V_h is the horizontal velocity of the droplet (m s^{-1}).

2.4 Data analysis

The multivariate analysis of variance (MANOVA) was used to evaluate the effects of operating pressure, nozzle diameter, and soil texture on the surface runoff rate, soil infiltration rate, infiltration depth prior to runoff, sediment yield, and changes in surface soil bulk density and porosity before and after irrigation, respectively. Mean values were separated using the Fisher's protected least significant difference (LSD) at the 0.05 level by using SPSS 20.0 software (IBM Corp., Armonk, NY, USA). Meanwhile, the Pearson correlation (assessed as significant at the $P < 0.05$ level) of this software was also employed to analyze the correlations among specific power, average droplet shear stress, and above soil physical properties under different working conditions. The Pearson correlation coefficient (r) was used to evaluate the degree of correlation between the variables (positive values represent positive correlation; negative values represent negative correlation). In addition, regression analysis was performed using the Origin 8.5 software (OriginLab, Northampton, MA, USA) and applied to develop the relationships between droplet indicators and soil physical properties. The coefficient of determination (R^2) was used to assess the goodness of fit of these relationships (a higher R2 value reflects a higher goodness of fit).

3. Results

3.1 Distributions of specific power and droplet shear stress

Fig. 3 presents the specific power and average droplet shear stress at water jet end under three nozzle diameters and two operating pressures, so as to make a comprehensive comparison of these two droplet indicators. Overall, there were the commonalities in distribution of the specific powers and average droplet shear stresses under different treatments, that is, the larger the operating pressure or nozzle diameter, the higher the specific power and average droplet shear stress. For instance, when the operating pressure was 103 kPa, the specific power and average droplet shear stress with a nozzle diameter of 7.94 mm were 0.549 W m-2 and 606.769 N m^{-2} larger than those of 3.97 mm nozzle diameter. The increase reached 558.92% and 34.74%, respectively. Whereas, the above values became 0.630 W m^{-2}, 800.881 N m^{-2}, 436.34%, and 31.87%, respectively under 138 kPa. These results demonstrated that the effect of nozzle diameter on the specific power was obviously greater than that on the average droplet shear stress. And with the increase of the operating pressure, these two droplet indicators under different nozzle diameters have increased to a certain extent in value, but the growth momentums with the nozzle diameter have decreased.

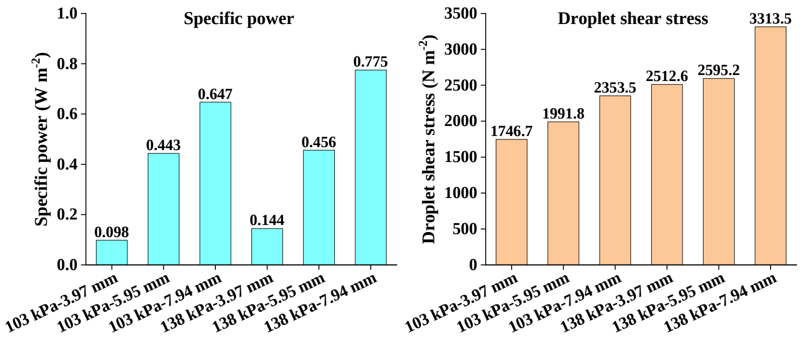

Figure. 3. Distributions of the specific powers and average droplet shear stresses under three nozzle diameters and two operating pressures.

Again, for the nozzle diameter of 3.97 mm, the specific power and average droplet shear stress at operating pressure of 138 kPa were increased by 47.01% and 43.85%, respectively, compared with those at 103 kPa. The corresponding values at the 7.94 mm nozzle diameter attained 19.67% and 40.79%, respectively. It was not difficult to observe that the operating pressure of the small-diameter nozzle had a slightly stronger effect on the specific power than that on the average droplet shear stress. Whereas, the operating pressure of the larger-diameter nozzle had the little effect on the specific power, even less than the effect on the average droplet shear stress. The reasons for the above phenomenon could be explained by the increase patterns of two droplet indicators under different working conditions (Fig. 3), that is, the specific power increased in a "roller coaster" manner, while the average droplet shear stress increased in a "step" manner. Generally speaking, the specific power under the operaing pressure of 138 kPa could only be guaranteed to be higher than 103 kPa at the same nozzle diameter. Once the nozzle diameter under 103 kPa increased, the specific power would exceed that of 138 kPa. In contrast, the average droplet shear stress for even smallest nozzle diameter at the 138 kPa operating pressure was higher than that for the largest nozzle diameter at 103 kPa. To sum up, it was the characteristics of "coexistence of similarities and differences" between specific power and average droplet shear stress that made it controversial to clarify the mechanisms of soil surface crusting, erosion, and infiltration of low-pressure sprinklers (Ghadiri and Payne, 2010; Caracciolo et al., 2012; Hui et al., 2021a).

3.2 Effects of specific power and droplet shear stress on surface runoff rate

Surface runoff rate is a key factor affecting soil erosion (El Kateb et al., 2013). Fig. 4 shows the variation of surface runoff rate with the irrigation time for two soil textures under the three nozzle diameters and two operating pressures of the sprinkler. It could be observed that no matter what treatment, the surface runoff rate increased initially and then gradually stabilized with the increase of the irrigation time. This phenomenon was inseparable from the infiltration characteristics of the soil itself. When the soil was in the early stage of sprinkler irrigation, almost all the water infiltrated due to its dryness and relatively large porosity. By increasing the irrigation time, the continuous impact of droplets on the soil gradually destroyed its structural stability. The surface soil particles undergone physical dispersion, displacement, pore filling, and compaction successively. As a result, the crusting of surface soil became more serious, and the soil infiltration was blocked, so the runoff rate tended to be stable. From the above analysis, the variation trend of surface runoff rate with the irrigation time in low-pressure sprinkler irrigation is actually universal for different treatments. Nonetheless, due to the various specific powers and average droplet shear stresses between treatments, there were the certain differences in occurrence and stability of runoff.

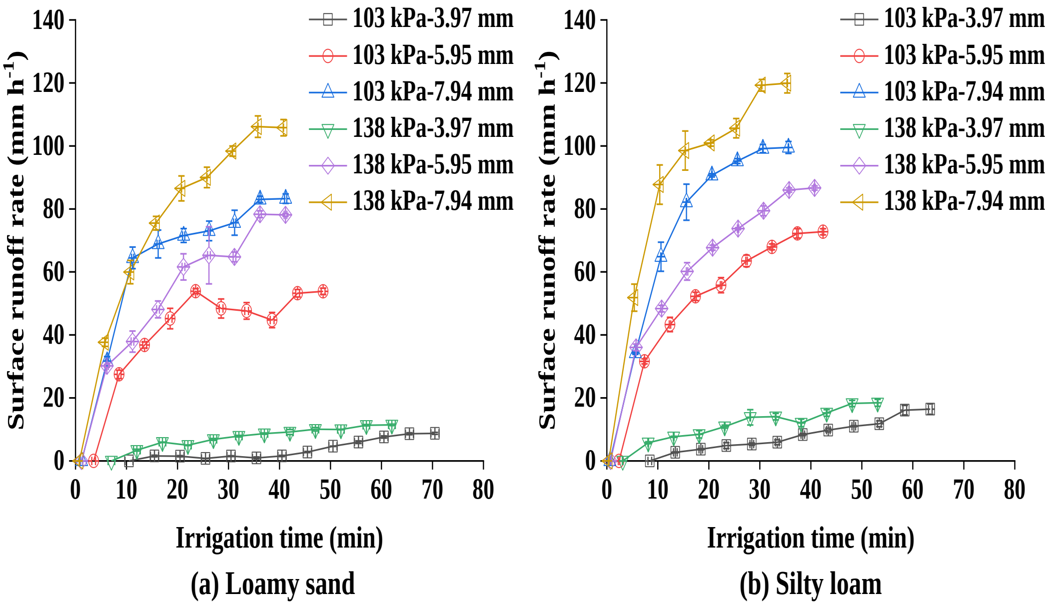

Figure. 4. Variations of the surface runoff rates with irrigation time under three nozzle diameters, two operating pressures, and two soil textures.

Fig. 5 presents the relationships between initial and steady runoff rates, times until runoff occur and stabilize and specific power and average droplet shear stress under different working conditions. In general, the larger specific power or average droplet shear stress corresponded with the higher initial and steady runoff rates and shorter times until runoff occur and stabilize. This result was consistent with Yan et al. (2011) using the D3000 sprinkler on sandy loam soil. According to statistics, the initial and steady runoff rates, times until runoff occur and stabilize under all treatments were distributed in the ranges of 1.57–51.85 mm h^{-1}, 8.75–119.92 mm h^{-1}, 0.37–10.49 min and 35.37–70.49 min, respectively. It was also found from Fig. 5 that the above four runoff indicators have the highly significant ($P<0.01$) correlations with the specific power, and also significantly ($P<0.05$) correlated with the average droplet shear stress. Therefore, although the surface runoff was closely related to the two droplet indicators of the specific power and average droplet shear stress. However, relatively speaking, the specific power seemed to be more realistic reflection of the surface runoff situation. This result could be explained by the relationship between specific power and water application rate of the D3000 sprinkler (Hui et al., 2022a).

Table 3 Initial and steady runoff rates, times until runoff occur and stabilize under three nozzle diameters, two operating pressures, and two soil textures.

Soil texture	Operating pressure（kPa）	Nozzle diameter（mm）	Initial runoff rate (mm h^{-1})	Steady runoff rate (mm h^{-1})	Time until runoff occur (min)	Time until runoff stabilize（min）
Loamy sand	103	3.97	1.57±0.25g[a]	8.75±0.33k	10.49±0.79a	70.49±0.79a
		5.95	27.47±1.34e	53.86±0.97h	3.56±0.37d	48.56±0.37e
		7.94	31.69±1.46d	83.28±1.50e	1.21±0.22f	41.21±0.22g
		Mean	20.24±14.16A[b]	48.63±32.52A	5.08±4.21A	53.42±13.20A

Soil texture	Operating pressure（kPa）	Nozzle diameter（mm）	Initial runoff rate (mm h-1)	Steady runoff rate (mm h-1)	Time until runoff occur (min)	Time until runoff stabilize（min）
	138	3.97	3.42±0.30fg	11.46±0.24j	7.04±0.66c	62.04±0.66c
		5.95	30.18±0.47d	78.11±0.45f	1.17±0.27f	41.17±0.27g
		7.94	37.68±1.31b	105.80±2.60b	0.77±0.03fg	40.77±0.03g
		Mean	23.76±15.61A	65.12±42.02A	2.99±3.06AB	47.99±10.54A
Silty loam	103	3.97	2.73±0.15g	16.45±1.64i	8.43±0.36b	63.43±0.36b
		5.95	31.61±0.79d	72.75±0.98g	2.39±0.15e	42.39±0.15f
		7.94	34.28±0.47c	99.51±1.91c	0.61±0.05fg	35.61±0.05h
		Mean	22.87±15.16A	62.91±36.71A	3.81±3.56AB	47.14±12.57A
	138	3.97	5.79±0.32f	18.44±1.10i	3.11±0.07d	53.11±0.07d
		5.95	36.07±1.03bc	86.66±0.67d	0.73±0.15fg	40.73±0.15g
		7.94	51.85±4.30a	119.92±3.08a	0.37±0.04g	35.37±0.04h
		Mean	31.23±20.39A	75.01±44.83A	1.40±1.29B	43.07±7.88A

Note: [a]Values in the same column with different lowercase letters are significantly different at a probability level of P<0.05; [b]Values in the same column with different uppercase letters are significantly different at a probability level of P<0.05.

Therefore, to further determine the effect of specific power on soil surface runoff, Table 3 shows the initial and steady runoff rates, times until runoff occur and stabilize under different treatments. It could be seen that the nozzle diameter had an obvious influence on the various indicators of surface runoff. Considering the operating pressure of 103 kPa under the loamy sand as an example, the initial and steady runoff rates under nozzle diameter of 7.94 mm were 30.12 and 74.53 mm h^{-1} higher than those of the nozzle diameter of 3.97 mm, respectively. Whereas, the times until runoff occur and stabilize of 7.94 mm were 9.28 and 29.28 min less than those of 3.97 mm, respectively.

These outcomes indicated that increasing the nozzle diameter not only significantly (P<0.05) increased the surface runoff rate, but also significantly (P<0.05) shortened the times until runoff occur and stabilize. Consequently, small-diameter nozzles should be selected preferably in the design of low-pressure sprinkler irrigation systems, so as to greatly reduce the specific power and thereby effectively minimize surface runoff.

Since the influence of operating pressure on the specific power was not as great as that of the nozzle diameter, the non-significant (P>0.05) difference in the surface runoff was observed between the two operating pressures. As shown in Table 3, the average differences of four runoff indicators (initial and steady runoff rates, times until runoff occur and stabilize) between 103 and 138 kPa under loamy sand were 3.52 mm h^{-1}, 16.49 mm h^{-1}, 2.09 min, and 5.43 min, respectively. For the silty loam, these difference values changed to 8.36 mm h^{-1}, 12.1 mm h^{-1}, 2.41 min, and 4.07 min, respectively.

In addition, it was also known from the table that the soil texture was crucial to the occurrence of surface runoff. Based on the comparison of runoff between loamy sand and silty loam under the operating pressure of 103 kPa and nozzle diameter of 7.94 mm, although the same specific power was applied to the two texture soil, the initial and steady runoff rates (31.69 and 83.28 mm h^{-1}) of loamy sand were smaller than those (34.28 and 99.51 mm h^{-1}) of silty loam. Suggesting that under the same sprinkler irrigation conditions, the less the soil sand content, the more serious the soil erosion (Sepaskhah and Shahabizad, 2010).

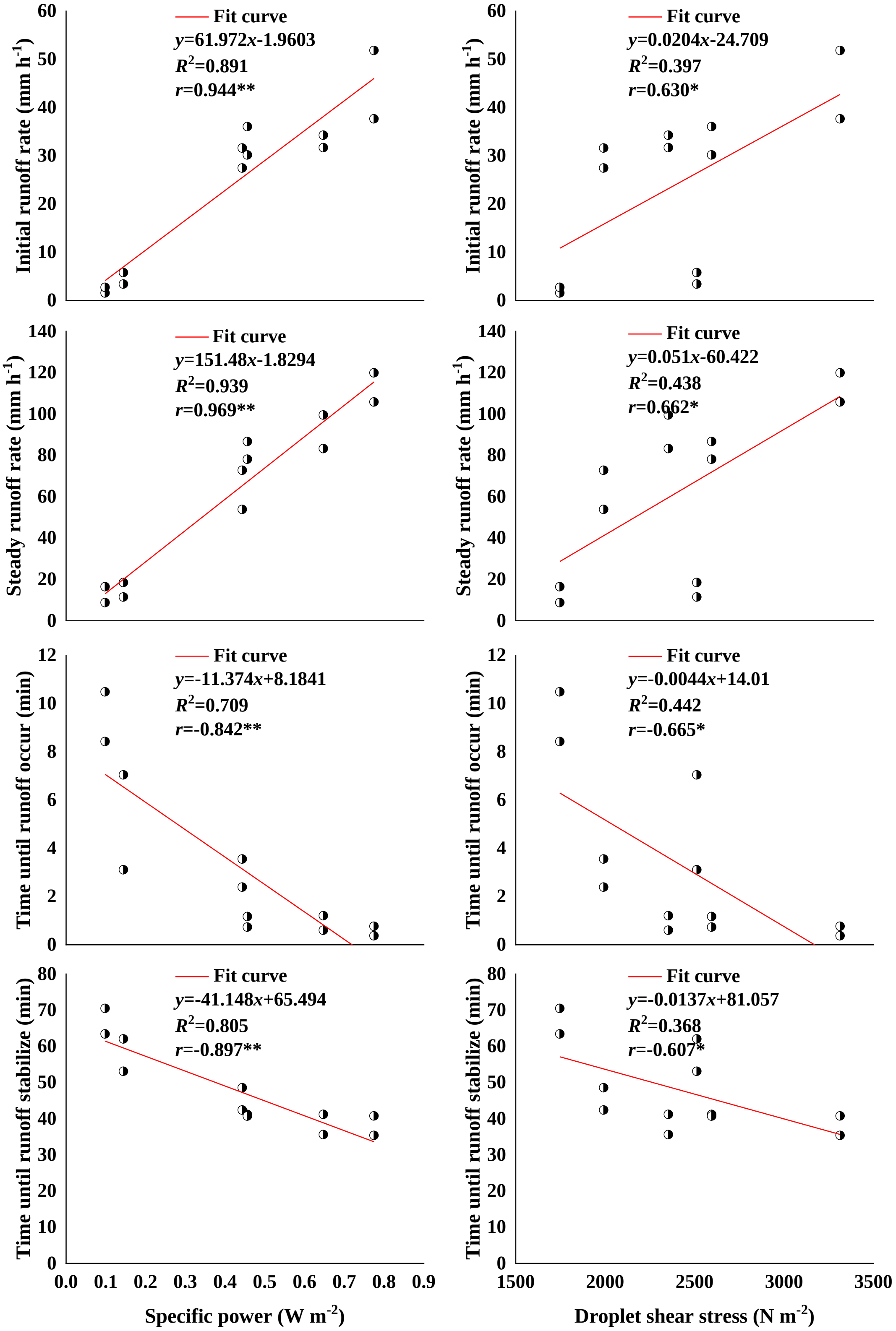

Figure. 5. Relationships between the initial and steady runoff rates, times until runoff occur and stabilize and specific power and average droplet shear stress under three nozzle diameters, two operating pressures, and two soil textures. Note: *Significant at a probability level of P<0.05; **Highly significant at a probability level of P<0.01.

3.3 Effects of specific power and droplet shear stress on soil infiltration rate

The soil infiltration rate affects the water uptake of sprinkler irrigation by the crops to a certain extent, which in turn affects the irrigation water use efficiency (Haghnazari et al., 2015). Generally, the opposite relationship is occurred between the soil infiltration rate and runoff rate. The higher the runoff rate, the lower the soil infiltration rate, and vice versa. Fig. 6 depicts the variations of infiltration rates with the irrigation time for two soil textures under the three nozzle diameters and two operating pressures of the sprinkler. It was clear that the soil infiltration under sprinkler irrigation was a changing process like surface runoff. The relatively large soil infiltration rate was occurred at the beginning of sprinkler irrigation, and with the extension of the irrigation time, the soil infiltration rate gradually decreased and eventually stabilized.

The observations of Thompson and James (1985) on the effect of droplet impact on the infiltration characteristics of a silt loam soil supported this process. Although the variation trend of soil infiltration rate in each working condition kept the same with the irrigation time, it was numerically different from each other. Considering the initial and steady runoff rates as an example (Table 4), when the soil texture and operating pressure were constant, the initial infiltration rate tended to increase significantly (P<0.05) as the nozzle diameter increased, while the steady infiltration rate did not (P>0.05). For example, regarding the operating pressure of 103 kPa in the loamy sand soil, the initial infiltration rate of nozzle diameter of 7.94 mm increased by 51.83 mm h^{-1} compared with that of 3.97 mm. The increase was as high as 157.74%. Whereas, the steady infiltration rate increased by 7.43 mm h^{-1}, the increase was only 28.93%. Thus, the nozzle diameter had a great influence on the initial infiltration rate.

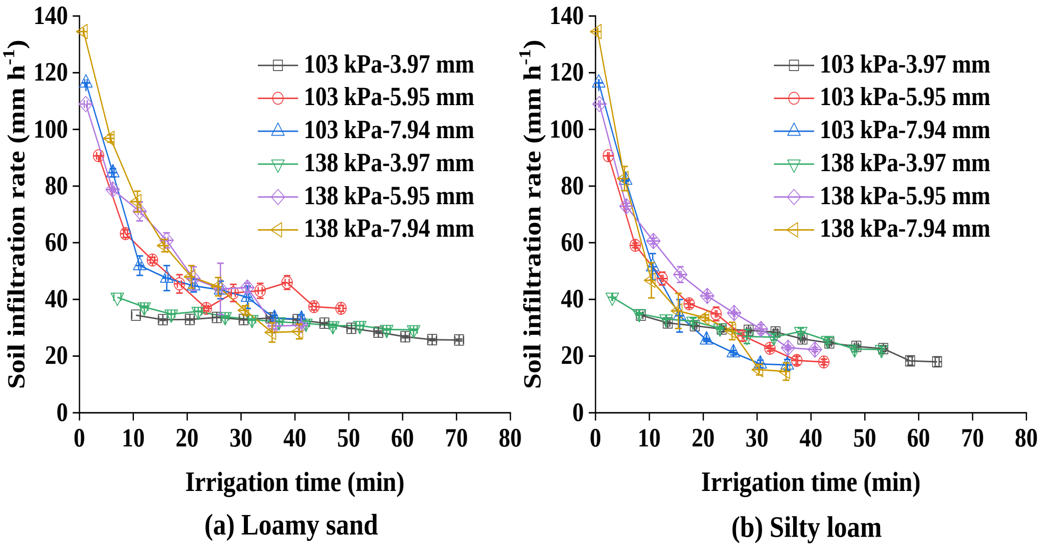

Figure. 6. Variations of the infiltration rates with irrigation time under three nozzle diameters, two operating pressures, and two soil textures.

It could also be seen from Table 4 that there was not significant (P>0.05) difference in the initial infiltration rates between operating pressures or soil textures. The average initial infiltration rates of 103 and 138 kPa attained 60.25 and 70.97 mm h^{-1} under loamy sand, while for silty loam the corresponding results became 57.62 and 63.50 mm h^{-1}, respectively. It was not difficult to find that the maximum difference among these four values was only 13.35 mm h^{-1}, which was much lower than that among the nozzle diameters under different working conditions (Mean of 52.34 mm h^{-1}). To sum up, the effect of operating pressure and soil texture on the initial infiltration rate was negligible relative to the nozzle diameter.

The part of reason for this result could be explained by the difference in specific powers or droplet shear stresses between various operating pressures (Fig. 3). Another reason was that at the beginning of sprinkler irrigation, both soils were dry and less damaged by droplets. Therefore, the irrigation water could be infiltrated quickly, so that the initial infiltration rate was not obviously affected by the soil texture. However, with the increase of the irrigation time, the effect of the soil texture became apparent when the soil infiltration rate reached a steady state. For example, the steady infiltration rate of loamy sand in Table 4 was significantly (P<0.05) higher than that of silty loam, which also implied that the higher the soil sand content, the greater the steady infiltration rate under same irrigation conditions.

Table 4 Initial and steady infiltration rates under three nozzle diameters, two operating pressures, and two soil textures.

Soil texture	Operating pressure（kPa）	Nozzle diameter（mm）	Initial infiltration rate (mm h^{-1})	Steady infiltration rate (mm h^{-1})
Loamy sand	103	3.97	32.86±0.25hi[a]	25.67±0.32d
		5.95	63.21±1.34e	36.82±0.97a
		7.94	84.68±1.47b	33.10±1.50b
		Mean	60.25±22.57A[b]	31.87±5.00A
	138	3.97	37.33±0.30g	29.29±0.24c
		5.95	78.78±0.47c	30.85±0.45bc
		7.94	96.80±1.32a	28.69±2.61c
		Mean	70.97±26.42A	29.61±1.64A
Silty loam	103	3.97	31.70±0.15i	17.97±1.65f
		5.95	59.07±0.79f	17.93±0.98f
		7.94	82.10±0.47b	16.86±1.91fg
		Mean	57.62±21.86A	17.59±1.46B
	138	3.97	34.96±0.31gh	22.31±1.09e
		5.95	72.89±1.02d	22.30±0.66e
		7.94	82.64±4.30b	14.56±3.08g
		Mean	63.50±21.92A	19.72±4.22B

Note: [a]Values in the same column with different lowercase letters are significantly different at a probability level of P<0.05; [b]Values in the same column with different uppercase letters are significantly different at a probability level of P<0.05.

In attempt to fully understand the effect of specific power and average shear stress on the soil infiltration rate, Fig. 7 shows the relationships between two droplet indicators and initial and steady infiltration rates. It was expected that the specific power and average shear stress were positively correlated with the initial infiltration rate, and the correlations reached highly significant ($P<0.01$) and significant ($P<0.05$) levels, respectively. On the one hand, it showed that the initial infiltration rate increased gradually with the increase of the specific power or average shear stress; on the other hand, it also revealed that the specific power seemed to have a greater effect than the average shear stress, although these two droplet indicators were very effective in adjusting the initial infiltration rate. These results were consistent with the previous outcomes of the initial runoff rate (Fig. 5). However, unlike the initial infiltration rate, the correlations between the steady infiltration rate and specific power and average shear stress were not significant ($P>0.05$). The steady infiltration rates were mainly in the small range of 14.56 to 36.82 mm h^{-1} under different treatments. Therefore, under low-pressure sprinkler irrigation, the steady infiltration rate actually had the little relationship with working conditions of the sprinkler. Even though the water application rate was relatively high for the larger operating pressure and nozzle diameter, the corresponding steady runoff rate would also increase. It was the dynamic relationship between water application rate and steady runoff rate that made the steady infiltration rates under various treatments, not apparently influenced by the impact of droplets.

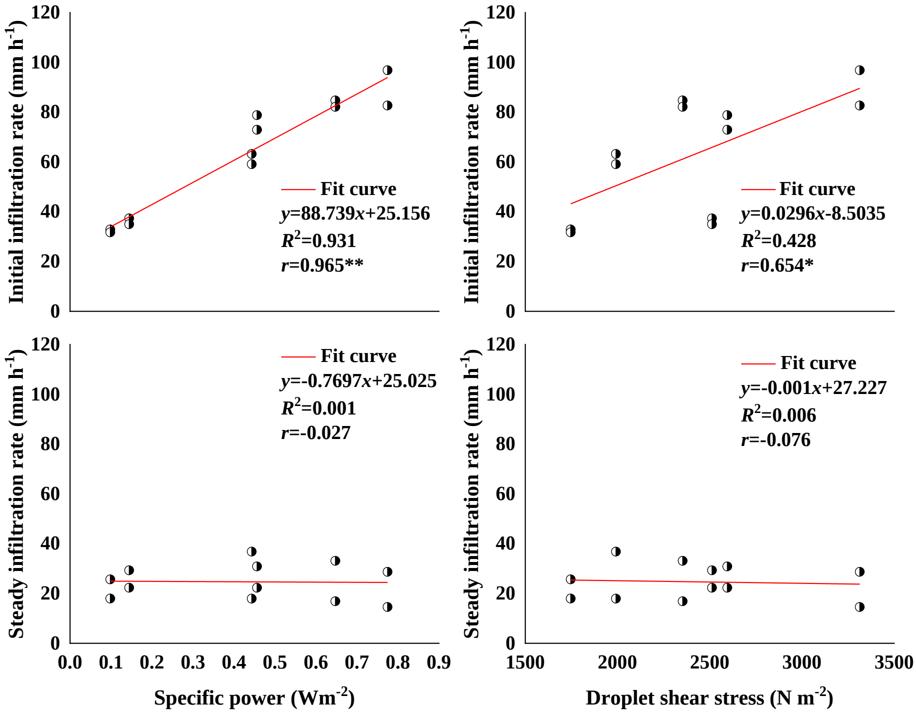

Figure. 7. Relationships between the initial and steady infiltration rates and specific power and average droplet shear stress under three nozzle diameters, two operating pressures, and two soil textures. Note: *Significant at a probability level of P<0.05; **Highly significant at a probability level of P<0.01.

3.4 Effects of specific power and droplet shear stress on infiltration depth prior to runoff

The infiltration depth prior to runoff is critical for determining the allowable water application rate without incurring runoff of soil (Kay, 1990). Fig. 8 shows the infiltration depth prior to runoff of the two soil textures under three nozzle diameters and two operating pressures of the sprinkler. It was essential to notice that regardless of the operating pressure and soil texture, the infiltration depth prior to runoff of 3.97 mm was the largest among the three nozzle diameters. Its infiltration depths prior to runoff under loamy sand reached 6.02 and 4.78 mm, respectively for the operating pressures of 103 and 138 kPa; while under silty loam the infiltration depths prior to runoff of the two operating pressures became 4.84 and 2.11 mm, respectively. This result suggested that for the same nozzle diameter, the infiltration depths prior to runoff varied significantly (P<0.05) between different operating pressures or soil textures. The greater operating pressure or less soil sand content could result in the smaller infiltration depth prior to runoff.

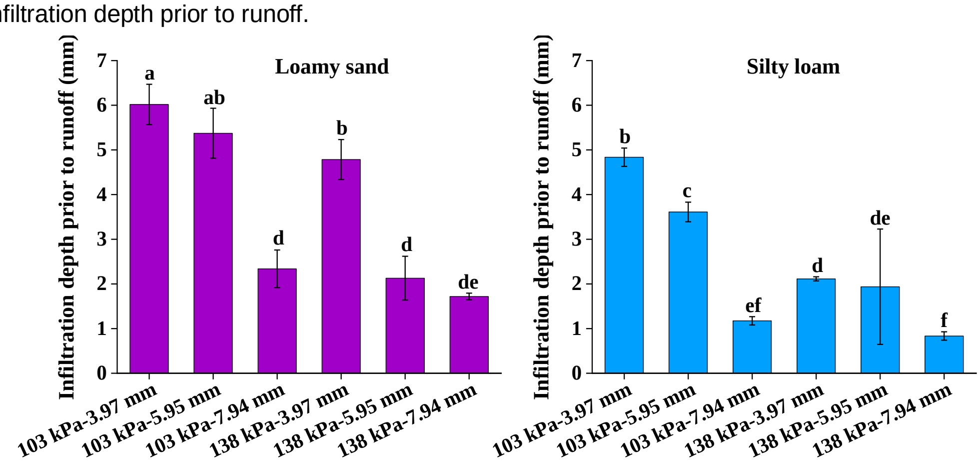

Figure. 8. Infiltration depths prior to runoff under three nozzle diameters, two operating pressures, and two soil textures. Note: **Highly significant at a probability level of P<0.01.

In addition, increasing the nozzle diameter also significantly (P<0.05) reduced the infiltration depth prior to runoff, but the reduction trend varied with the operating pressure and soil texture. It was not difficult to find from Fig. 8 that the infiltration depths prior to runoff under the three working conditions of 103 kPa in loamy sand, 103 and 138 kPa in silty loam always presented a trend of the slow and then fast reduction with increase of the nozzle diameter. For example, the infiltration depths prior to runoff of these three working conditions under the nozzle diameter of 5.95 mm reduced by 0.64, 1.23, and 0.18 mm compared with the 3.97 mm nozzle, respectively, and the decreases were only 10.71%, 25.34%, and 8.33%. Whereas, the infiltration depths prior to runoff of the 7.94 mm nozzle were 3.04, 2.44, and 1.10 mm lower than those of the 5.95 mm nozzle, and the decreases were as high as 56.49%, 67.47%, and 56.93%, respectively. In contrast, the reduction trend of 138 kPa operating pressure under loamy sand was exactly opposite to the above three working conditions. Its infiltration depth prior to runoff for the nozzle diameter of 5.95 mm was 55.51% lower than that of the 3.97 mm nozzle, while the reduction of the 7.94 mm nozzle attained 19.28% compared with the 5.95 mm nozzle. Consequently, without considering the influence of factors such as the operating pressure and soil texture, the variation trend of infiltration depth prior to runoff with the nozzle diameter was very consistent with that of the specific power (Fig. 3). This was also the reason for highly significant (P<0.01) negative correlation between the specific power and infiltration depth prior to runoff in Fig. 9.

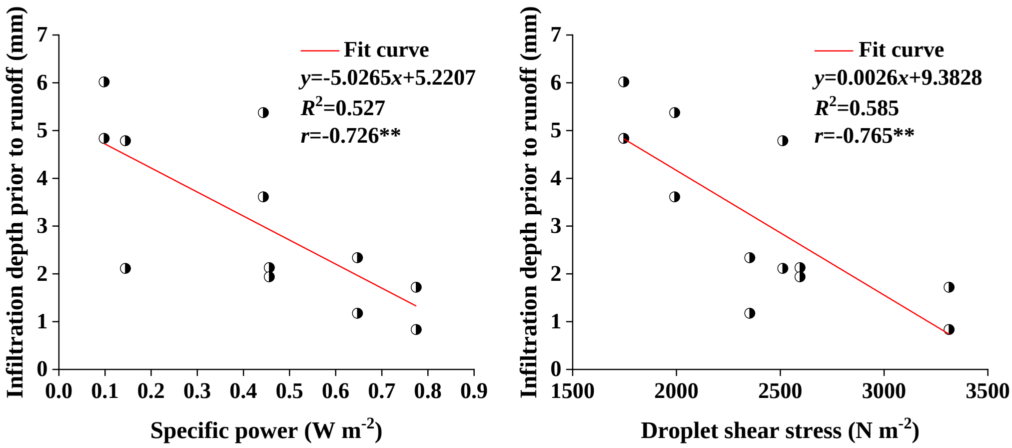

Figure. 9. Relationships between the infiltration depth prior to runoff and specific power and average droplet shear stress under three nozzle diameters, two operating pressures, and two soil textures. Note: **Highly significant at a probability level of P<0.01.

However, it was worth noting that the specific power was not the most important factor affecting the infiltration depth prior to runoff, and its correlation with the infiltration depth prior to runoff (*r*=-0.726) was slightly worse than that of the average droplet shear stress (*r*=-0.765). It could be seen from Fig. 8 that under the same soil texture, except for the obviously lower infiltration depth prior to runoff under the working condition of 103 kPa-7.94 mm (operating pressure-nozzle diameter), the infiltration depths prior to runoff for other nozzle diameters under the operating pressure of 103 kPa were larger than those of the all nozzle diameters at 138 kPa. This result was in accordance with the general trend of average droplet shear stress with the nozzle diameter and operating pressure (Fig. 3). This was not surprising since the increase of the droplet shear stress could accelerate the disintegration, fragmentation, and water absorption and expansion of soil particles. As a result, the porosity of the surface soil decreased rapidly, which led to the relatively lower infiltration depth prior to runoff.

3.5 Effects of specific power and droplet shear stress on sediment yield

When surface runoff occurs, a certain amount of sediment will be taken away, and the higher sediment yield also indicates more severe soil erosion (De Vente and Poesen, 2005). Fig. 10 shows the sediment yields of two soil textures under the three nozzle diameters and two operating pressures of the sprinkler. Obviously, except for 138 kPa-3.97 mm, which had a lower sediment yield, the sediment yields of the other working conditions under both soil textures followed a gradual increasing trend from 103 kPa-3.97 mm to 138 kPa-7.94 mm (Fig. 10). This was similar to the variation trend of the average droplet shear stress (Fig. 3). It was verified that a highly significant (P<0.01) correlation was found between the sediment yields and average droplet shear stresses under different treatments, and its r value was as high as 0.844 (Fig. 11). Therefore, the average droplet shear stress of the low-pressure sprinkler was closely related to the sediment yield.

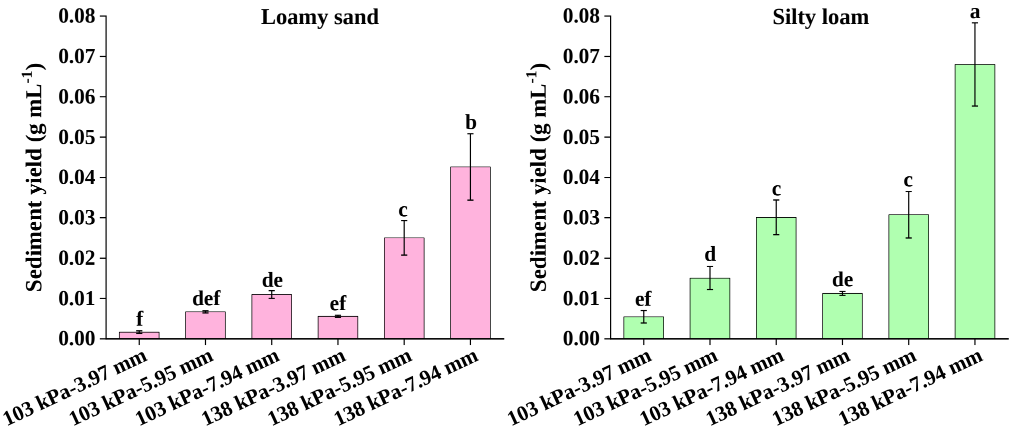

Figure. 10. Sediment yields under three nozzle diameters, two operating pressures, and two soil textures. Note: *Significant at a probability level of P<0.05.

In addition, it could be observed from Fig. 11 that the specific power and sediment yield also had a highly significant (P<0.01) correlation. Whereas, its *r* value (0.775) was relatively low compared to the correlation between the average droplet shear stress and sediment yield. Therefore, from the experimental results of nozzle diameter, operating pressure, and soil texture three aspects, the average droplet shear stress was more suitable for predicting the sediment yield in low-pressure sprinkler irrigation systems than the specific power. However, apart from the other two factors, only considering the sediment yields under different nozzle diameters, the prediction effect of the specific power seemed to be better (Fig. 3). Furthermore, it was essential to notice from Fig. 10 that no matter what operating pressure and soil texture were used, the sediment yield with nozzle diameter of 3.97 mm was always lowest. The larger nozzle diameter was associated with the higher specific power, which in turn leaded to the more sediment yield. It was found that for two operating pressures (103 and 138 kPa), the ranges of sediment yields at each nozzle diameter were 0.002–0.011 and 0.006–0.043 g mL^{-1} under loamy sand, respectively. The corresponding values under silty loam were 0.005–0.030 and 0.011–0.068 g mL^{-1}, respectively. This outcome suggested that the overall effect of operating pressure and soil texture on the sediment yield was still relatively significant (P<0.05), and the larger operating pressure or lower soil sand content could bring the greater sediment yield. To sum up, for silty loam, in the case of meeting the requirements of sprinkler irrigation, the low-pressure sprinkler should choose the smaller operating pressure and nozzle diameter to reduce soil erosion. Whereas, the operating pressure and nozzle diameter could be increased appropriately in loamy sand.

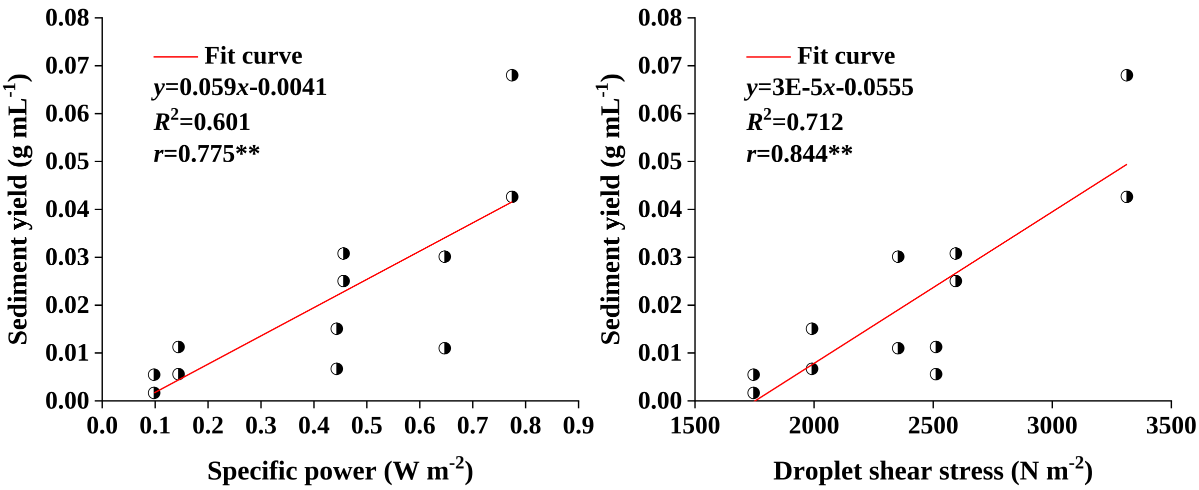

Figure. 11. Relationships between the sediment yield and specific power and average droplet shear stress under three nozzle diameters, two operating pressures, and two soil textures. Note: **Highly significant at a probability level of P<0.01.

3.6 Effects of specific power and droplet shear stress on surface soil bulk density and porosity

The continuous impact of sprinkler droplets can destroy the originally stable structure of soil surface. The large soil particles are constantly decomposed into small particles and enter the soil pores with water, thereby changing the soil bulk density and porosity (Tarchitzky et al., 1984; Lehrsch et al., 2005). Table 5 illustrates the changes in surface soil bulk densities and porosities before and after irrigation of two soil textures under the three nozzle diameters and two operating pressures of the sprinkler. Regardless of the soil texture, operating pressure, and nozzle diameter, the bulk density of surface soil after irrigation increased compared with that before irrigation, while the soil porosity decreased correspondingly. This finding was consistent with Silva et al. (2006) on a Mediterranean soil and Yan et al. (2011) on a sandy loam with low-pressure sprinkler irrigation. For example, for the two operating pressures of 103 and 138 kPa under silty loam, their surface soil bulk densities after irrigation increased averagely by 0.17 and 0.21 g cm^{-3}, respectively compared with those before irrigation, and the corresponding soil porosities decreased by an average of 6.53% and 7.80%, respectively. The above results also suggested that under the same soil texture, even though the operating pressure had no significant ($P>0.05$, Table 5) effect on the bulk density and porosity of surface soil after irrigation, the enlargement in the operating pressure increased the soil bulk density and decreased the porosity.

Table 5 Surface soil bulk densities and porosities before and after irrigation under three nozzle diameters, two operating pressures, and two soil textures.

Soil texture	Operating pressure (kPa)	Nozzle diameter (mm)	Surface soil bulk density (g cm^{-3})			Surface soil porosity (%)		
			Before irrigation	After irrigation	Increase	Before irrigation	After irrigation	Decrease
Loamy sand	103	3.97	1.40	1.43±0.01f[a]	0.03±0.01f	47.17	45.91±0.22a	1.26±0.22f
		5.95	1.40	1.50±0.01e	0.10±0.01e	47.17	43.54±0.34b	3.63±0.34e
		7.94	1.40	1.53±0.00d	0.13±0.00d	47.17	42.18±0.04c	4.99±0.04d
		Mean	1.40	1.49±0.04B[b]	0.09±0.04B	47.17	43.88±1.65A	3.29±1.65B
	138	3.97	1.40	1.46±0.02f	0.06±0.02f	47.17	45.03±0.58a	2.14±0.58f
		5.95	1.40	1.52±0.02de	0.12±0.02de	47.17	42.51±0.66c	4.66±0.66d
		7.94	1.40	1.56±0.01c	0.16±0.01c	47.17	41.15±0.41d	6.02±0.41c
		Mean	1.40	1.51±0.05B	0.11±0.05B	47.17	42.90±1.77A	4.27±1.77B
Silty loam	103	3.97	1.40	1.51±0.01de	0.11±0.01de	47.17	43.09±0.49bc	4.08±0.49de
		5.95	1.40	1.58±0.02c	0.18±0.02c	47.17	40.49±0.77d	6.68±0.77c
		7.94	1.40	1.63±0.01b	0.23±0.01b	47.17	38.34±0.46e	8.83±0.46b
		Mean	1.40	1.57±0.06A	0.17±0.06A	47.17	40.64±2.12B	6.53±2.12A
	138	3.97	1.40	1.53±0.02d	0.13±0.02d	47.17	42.14±0.58c	5.03±0.58d
		5.95	1.40	1.61±0.02b	0.21±0.02b	47.17	39.11±0.94e	8.06±0.94b
		7.94	1.40	1.67±0.02a	0.27±0.02a	47.17	36.87±0.81f	10.30±0.81a
		Mean	1.40	1.61±0.06A	0.21±0.06A	47.17	39.37±2.39B	7.80±2.39A

Note: [a]Values in the same column with different lowercase letters are significantly different at a probability level of $P<0.05$; [b]Values in the same column with different uppercase letters are significantly different at a probability level of $P<0.05$.

In addition, it could be seen from Table 5 that the nozzle diameter and soil texture had the significant ($P<0.05$) effects on bulk density and porosity of the surface soil after irrigation. Considering the two working conditions of 103 kPa-3.97 mm and 103 kPa-7.94 mm as examples, the bulk density and porosity of surface soil after irrigation were 1.43 g cm-3, 1.53 g cm-3, 45.91%, and 42.18%, respectively under loamy sand. For silty loam, the above values were changed to 1.51 g cm^{-3}, 1.63 g cm^{-3}, 43.09%, and 38.34%, respectively. This result mainly explained two problems. One was that the bulk density of surface soil tended to increase as the nozzle diameter increased, while the porosity decreased accordingly; the other was that the bulk density and porosity of silty loam after irrigation were larger and smaller than those of loamy sand, respectively, indicating that under the same sprinkler irrigation conditions, the lower the soil sand content, the greater the damage by droplets.

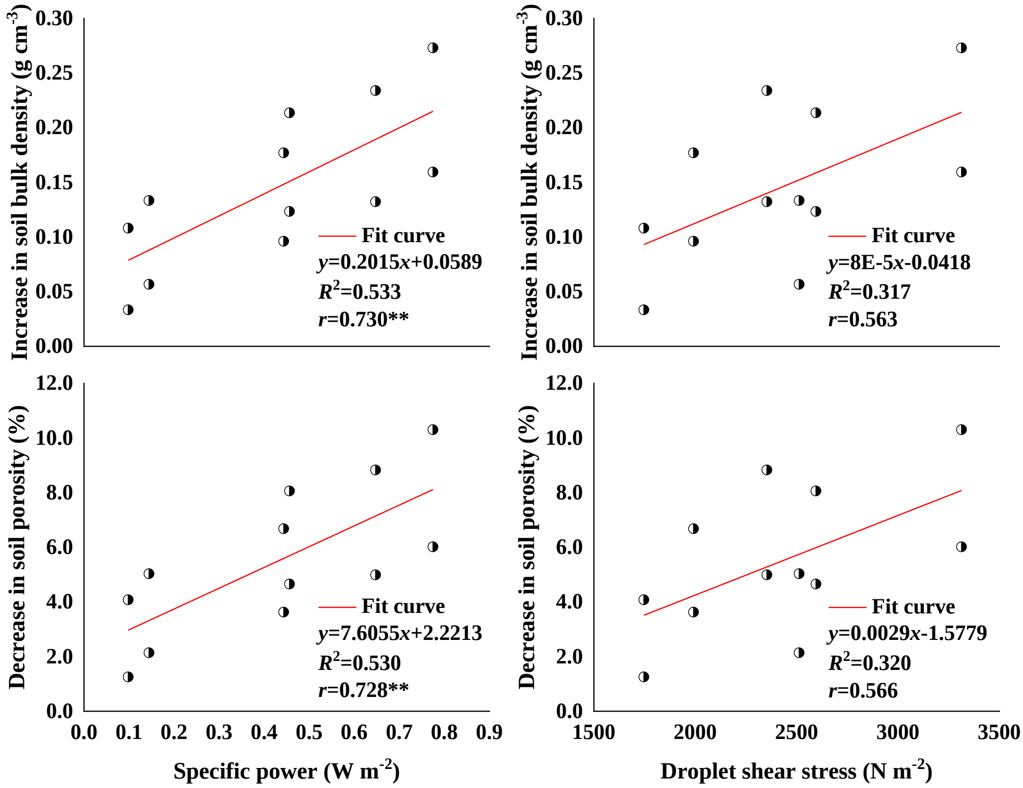

Figure. 12. Relationships between the increase in surface soil bulk density and decrease in surface soil porosity and specific power and average droplet shear stress under three nozzle diameters, two operating pressures, and two soil textures. Note: **Highly significant at a probability level of P<0.01.

To determine the effect of sprinkler droplets on the physical properties of soil surface under different treatments, Fig. 12 shows the relationships between increase in surface soil bulk density and decrease in surface soil porosity after irrigation and specific power and average droplet shear stress. It was notable to observe that the specific power and average droplet shear stress had the completely different performances in affecting the physical properties of soil surface. The correlations between the specific power and increase in the soil bulk density and decrease in the porosity were highly significant (P<0.01), while the average droplet shear stress had no correlation with the above two soil indicators (P>0.05). This was mainly because the specific power was closely related to the water application rate. In general, the larger specific power corresponded with the higher initial infiltration rate (Fig. 7), which increased the probability of small-sized sediment entering the soil pores with water flow. In summary, in the design of low-pressure sprinkler irrigation systems, the small nozzle diameter and operating pressure should be selected preferably to reduce the specific power.

4. Conclusions

For various nozzle diameters, operating pressures, and soil textures, the effects of specific power and droplet shear stress on the physical properties of soil surface was similar. In general, the enlargement in the specific power or average droplet shear stress could increase the initial and steady runoff rates and decrease the time until runoff occur and stabilize. In addition, the greater the specific power or average droplet shear stress was, the higher the initial infiltration rate, sediment yield, and surface soil bulk density were. However, this also led to the lower infiltration depth prior to runoff and surface soil porosity. Comparing the correlations between droplet indicators and soil physical properties, it could be observed that the correlations between the specific power and initial and steady runoff rates, times until runoff occur and stabilize, initial infiltration rate, and increase in the soil bulk density and decrease in the soil porosity after irrigation were better than those of average droplet shear stress. Nonetheless, the correlations with soil physical properties such as the infiltration depth prior to runoff and sediment yield were performed relatively poor. Overall, the specific power was more suitable for accurately predicting the soil erosion under low-pressure sprinkler irrigation than the droplet shear stress. Furthermore, considering the positive influences of nozzle diameter and operating pressure on the specific power and average droplet shear stress, to minimize the risk of soil erosion in low-pressure sprinkler irrigation engineering, the smaller nozzle diameter (3.97 mm) and operating pressure (103 kPa) should be selected preferably. In addition to the above measures, it was also recommended to increase surface vegetation coverage or spray an appropriate amount of soil amendments for the soils with low sand content.

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OUTLOOK: USE OF TWW (TREATED WASTE WATER) FOR AGRICULTURE VIA MICRO IRRIGATION SYSTEM: A CASE STUDY

Mr Yewalekar Dilip[1], Ms Kinge Manisha[2]

ABSTRACT

Wastewater treatment means the removal of impurities from wastewater, before reaching aquifers or natural bodies of water such as rivers, lakes, and Oceans. *'UNWWDR2017'* report said more than 80 percent of the world's wastewater flows back into the environment without being treated and unfortunately proper data on wastewater treatment and reuse is not available at this stage. Some European Countries has made a significant contribution to wastewater treatment and reuse for agriculture, construction, and cleaning purpose.

TWW management is the prime target of the UN's Sustainable Development Goals *(SDG 6.3)* & environment protection *(COP26),* which explicitly focus on reducing water pollution, treatment of wastewater, and re-reuse for agriculture, and landscape, forestry, and gardens. Recently, 197 countries signed the agreement on 10th Nov 2022, the UNEP, Glasgow, and committed to achieving the target of SDG 6.3 by 2030.

Since 1980, India has initiated the treatment of wastewater and re-use for irrigation of lawns, gardens, landscapes, and forestry at Chennai Municipal Corporation. Many research institutes e.g. Indian Agricultural Research Institute, Karnal, University of Agricultural Science, Dharwad, have also carried out research work on the use of TWW for agriculture purposes.

Ministry of Jal Shakti (Department of Water Resource), Government of India, formulated National Frame Work on Safe Reuse of Treated Water (SRTW) with the vision, of 'widespread and safe reuse of treated used water in India that reduces the pressure on scarce freshwater resources, reduces pollution of the environment and risks to public health, and achieves socio-economic benefits by adopting a sustainable circular economy approach. It heralds a shift from existing perspectives on waste to a new understanding of Our Water *(Apna Jal)*'.

This policy is complementary to previous & current policies of State Governments, CPCB (Central Pollution Control Board), SPCB (State Pollution Control Board), and Water Supply Department also interrelated to National Water Policy (NWP2020), National Urban Sanitation Policy (NSUP2008), National Environmental Policy (NEP 2006), National Faecal Sludge and Septate Management Policy (FSSM, 2017). These policies are complementary to Goal 3 of the National Water Mission (NWM) which emphasizes promoting the recycling of used water for meeting the water needs of urban areas.

Under the framework of the Ministry of Jal Shakti, Haryana State Government has taken an initiative and implemented 'the use of TWW for agriculture via Drip & Sprinkler Irrigation'. The concerned article describes the algorithm to design Micro (Drip)/Sprinkler Irrigation systems for agriculture using TWW, validating norms specified by various governments along with briefing wastewater treatment, water quality parameters for crop suitability, and minimum residual level (MRL) and, a case study. It also indicates the pros-cons, hurdles & limitations on the acceptance level of the public. It helps to clear doubts among the society and encourages State/Central Government, Private companies, and Growers to adopt the model to overcome water scarcity and address the environmental & water pollution issues.

Keywords: Wastewater, European Countries, Glasgow, SDG 6.3, Reuse of Treated Water, Agricultural

1.0 Introduction

Because of the lack of a political will, technical know-how, R & D database, and mindset, this subject is least highlighted at a national–international forum. This is the time to formulate the policy to implement a proper TWW project at Government, Private levels & PPP. Some of the metros also implemented the TWW irrigation projects for various crops, as shown in Table 1. Haryana & Punjab State governments have started implementing the use of TWW for agriculture on a mass scale.

Growers are coming forward to use TWW for agriculture and in this context representative case study (Table 3 & photos) of one of the growers is highlighted in this article and will help to encourage other state governments and growers to apply such a project in their territory.

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Table 1. Major Irrigation project TWW (Ref: International Water Management Institute (IWMI), Resource Recovery & Reuse Series 8)

City	Crop cultivated	Increase in yield (%)	Savings in fertilizer (%)
Indore	Wheat (Rabi)/ vegetables (summer)	30-40%	50%
Nagpur	Wheat (Rabi)/ vegetables (summer)	30-40%	33%
Jaipur	Wheat (Rabi)/ vegetables (summer)	30-40%	50%
Bangalore	Rice (Rabi), Sapota & flowers	30-40%	100%
Delhi	Okra (summer)	67%	60%

2.0. WWS (World Water Stress)

In the world, 18.4 % of total renewable freshwater resources available are being withdrawn and 72% of all water withdrawals are used by agriculture, 16% by municipalities for households, and 12 % by industries. Including India, many Asian countries reach high water stress (Fig.1), which means there is not enough water to cater to the need of agriculture, community, and industries. So It is necessary to use TWW for agriculture to fulfil the remaining fulfill during water stress. With efficient water distribution systems and sustainable systems culture, the reuse of wastewater is a key strategy for reducing water stress.

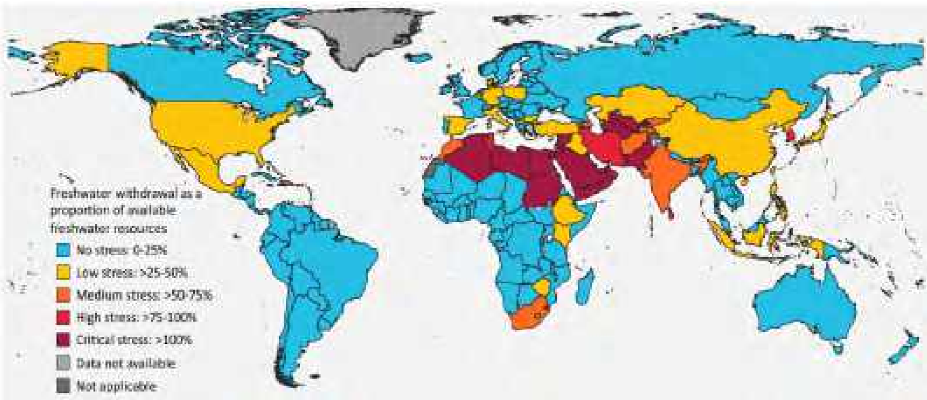

Figure 1. Water Stress Countries (Ref: UN Water Report July 2021).

3.0. Agriculture water pollution

Agriculture is the world's largest consumer of water. Over the half century, agriculture has expanded and intensified in order to meet the increasing food demand triggered mainly by population growth and changes in diet. The area equipped for irrigation has more than doubled, from circa 1.4 million km^2 in 1961 to circa 3.2 million km^2 in 2012 *(ref-Aquastat, 2014)*. Agriculture intensification has frequently come with increased soil erosion, higher sediment loads in water, and excessive use (or misuse) of agricultural inputs (e.g. pesticides and fertilizers) to increase productivity. When the use of such products exceeds the assimilation capacity of agricultural systems, it results in higher pollution loads to the environment. The excess use of irrigation water also enhances the agricultural wastewater flows back into water bodies in the form of deep percolation to aquifers and runoff to surface waters**.**

4.0. Principle Stages of Waste Water Treatment

There are three levels of wastewater treatment: primary, secondary, and tertiary (or advanced).

- Collection tank: To collect raw water /wastewater.
- Bar Screen /Grit: To separate solid matters, and debris.
- Trap: To separate solid matters.
- Primary clarifier
- Aeration tank

- Nutrient removal (if)
- Secondary clarifier
- Disinfection
- Final produce.
- Sludge holding tank.
- Sludge Treatment.

4.1. Primary treatment

Primary treatment removes physical debris through the process of screening. Suspended particles that pass through screens and grit chambers are removed from the sewage in sedimentation tanks, called primary clarifiers.

4.2. Secondary treatment

Secondary treatment removes the soluble organic matter and suspended solids escape primary treatment. Removal is usually accomplished by biological processes with microbes.

4.3. Disinfections

Disinfection is the last step prior to discharge of the sewage effluent into a water body which destroys any remaining pathogens in the effluent & protects public health, is usually done by injection of chlorine-based chemicals.

5.0 TWW for Irrigation

The success of (TWW) Treated Waste Water use for crop production largely depends on adopting appropriate strategies aimed at optimizing crop yields and quality, maintaining soil productivity, and safeguarding the environment. Several alternatives are available to use TWW for agriculture via various irrigation methods. The user should have prior information on TWW supply and its quality as per Table 2 for reference to ensure the formulation and adoption of an appropriate on-farm management strategy.

Table 2. TWW Quality Norms (Ref-PPCB

Sr	Parameters	TWW Standard Norms
1.	Temperature	Not more than 50C.
2.	pH	5 - 9
3.	BoD	<= 10 ppm
4.	COD	<= 50 ppm
5.	TSS	<= 20 ppm
6.	Sulfates	<= 200 ppm
7.	TKN	<= 50 ppm
8.	Faecal coliform	<= 100 MPN/100 ml
9.	Total Phosphorus	<= 2 ppm
10.	Ammonical Nitrogen	<= 20 ppm
11.	SAR	<=3.5 ppm
12.	EC	<=2000 micro siemens/cm
13	RSC	<= 2.5 meq/l

5.1. Advantages the of use of TWW for agriculture.

- Higher crop yield, year-round agriculture production.
- Various crops can be grown.
- Recycles organic matter and other nutrients used in soil.
- Reduces the use of fertilizer.
- Acts as a low-cost wastewater disposal method that can also be hygienic (under controlled conditions).
- Avoids discharging pollutants to surface water bodies and Increases the economic efficiency of investments in wastewater disposal and irrigation.
- Conserves freshwater sources and reduces negative impacts on surface water bodies.
- Can recharge aquifers through infiltration.
- Improve soil properties –soil fertility and texture.
- The cost of pumping wastewater from nearby channels is lower than the cost of pumping groundwater.
- If offers additional benefits such as greater income generation from cultivation and marketing of high-value crops which contributes to improved nutrition and better education opportunities for children.

5.2. Limitations of using TWW for agriculture irrigation

- To maximize the benefits and minimize drawbacks, wastewater reuse must be carefully planned.
- Because the impact of pollution is generally less and takes longer in soils (and aquifers) than in surface water.
- Water salinity and metal content in soils are increased in the long term.
- Storage capacity is needed to adapt/reconcile continuous wastewater production with crops water demand.
- Under non-controlled conditions
  - Pathogens contained in wastewater can cause health problems for humans and cattle.
  - Some substances that may be present in wastewater can be toxic to plants, cattle or human-consuming crops.
  - Some substances that may be present in wastewater can reduce soil productivity.
  - Infiltration of wastewater to aquifers may cause aquifer pollution with pathogens and organic matter.

6.0. Agriculture Key Principles

Following key principles shall be kept in mind before deciding the use of TWW for agriculture

a. Being an agrarian economy, this is a very compelling use for India, but should never be used for edible crops.

b. The use of untreated wastewater for whatever form of agriculture leads to a situation where the TWW entering another basin from its parental basin creates issues of water rights and as far as possible, inter-basin transfer of such reuse is not to be encouraged.

c. Agricultural use being more pertinent in rural settings, local sewage is best treated with stabilization ponds followed by maturation ponds.

d. Rotational crop pattern shall be investigated for an all the year round utilization and designed such that the runoff of treated sewage in summer is minimized.

e. Specific limitations on individual parameters when the TWW is to be considered for irrigation are addressed herein.

7.0. Irrigation- Furrow/Drip/Sprinkler Irrigation System

The different types of irrigation methods have to be selected based on available water, climate, soil type, crop to be grown, and the ability of the farmer to manage the crop & irrigation system. However, when using TWW as a source of irrigation other factors, such as contamination of plants and harvested product, farm workers the environment, and salinity and toxicity hazards, need to be assessed. The following basic parameters should be accounted for while using TWW for agriculture:

- Required amount of water should be applied.
- Water quality should be acceptable.
- Water application should be properly scheduled.
- Appropriate irrigation methods should be used;
- Salt accumulation in the root zone should be prevented by means of leaching;
- Rise of the water table should be controlled by means of appropriate drainage;
- Plant nutrients should be managed in an optimal way.
- Selection of salt-tolerant crops.
- Proper wetting of root zone.
- Higher application efficiency and minimum wastage of water
- Potential to contaminate farm workers and the environment.

7.1. Types of Irrigation Systems

a. Furrow irrigation

Water is applied between ridges (e.g. level and graded furrows, contour furrows, corrugations, etc.). The water reaches the ridge, where the plant roots are concentrated, by capillary action. This method can reduce crop contamination since plants are grown on the ridges, but complete health protection cannot be guaranteed. Contamination of farm workers is potentially medium to high.

b. Drip Irrigation

Water is applied around each plant or a group of plants so as to wet locally and the root zone only (e.g. drip irrigation, bubblers, micro-sprinklers, etc.). The application rate is adjusted to meet evapotranspiration needs so that percolation losses are minimized.

c. **Sprinkler irrigation**

Water is applied in the form of a spray and reaches the soil very much like rain (e.g. portable and solid set sprinklers, traveling sprinklers, spray guns, center-pivot systems, etc.). The rate of application is adjusted so that it does not create ponding of water on the surface.

7.2. Components of Micro Irrigation System

The type and sequence of components, in irrigation, are typically the same for all field sizes as indicated in figure 2 based on field size, component sizes may vary. The actual selection of a specific component generally needs to be made on a case-by-case basis. A brief description of the main components is given below.

i. Pumping system

The role of the pumping system is to lift & transport water from the water source to the field through the distribution system. Pumping systems may be classified as electric-powered, gas/diesel-powered, and solar-powered systems.

ii. Piping Network

The function of piping network is to convey the water from the source to the field. Distribution systems may be above ground or underground. Pipes are most commonly made of PVC or HDPE. The size and shape of the distribution system may vary widely from field to field.

iii. Polytube

Polytubes are made of LLDPE material, flexible and strong in natures, conveys water from sub-main pipes to each crops rows. Polytubes are spread in the entire field at a spacing that depends on the row-to-row distance of the crop.

iv. Emitters /Sprinklers

Emitters/Sprinklers are supplies near to root zone of crops. Selection of emitters/sprinklers depends on soil type, crop, spacing, age, root zone, and crop water requirement.

v. Filtration system

The filtration system removes physical particles present in water. Different types of filters are used based on the type of particles present in the water. Media (Sand) filters are used with surface water when large amounts of organic matter need to be filtered out. Screen filters or disc filters may be used to filter water from balance physical impurities present after the Sand filter and 100-micron stainless steel screens are used for this purpose. When the water contains sand, sand separators are used.

vi. Fertilizer Injectors

Injectors allow to injection of fertilizer & chemicals as per crop demand.

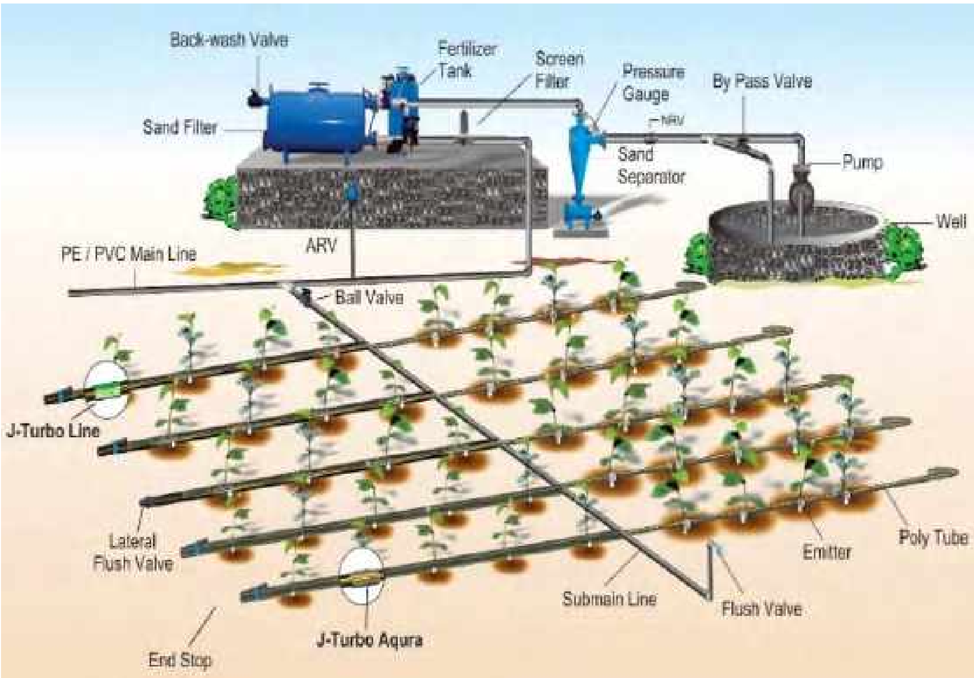

Figure 2. Architect of Micro Irrigation System

8.0 Government Policy

Government policy on TWW available to farmers for unrestricted irrigation or to irrigate public parks and urban green areas is a deciding factor to promote the use of TWW at a large scale and minimize the water stress and pollution of the environment.

Option of blending TWW with other water supplies in ratio (50:50 or 60:40) like canal water, groundwater or surface water, is normally advantageous in respect of allowing greater flexibility, increased financial security, and more efficient use of the wastewater throughout the year for various crops.

Table 3. Case study: Use of TWW for Agriculture- Irrigation, STP-CADA, Shahabad, Haryana.

Sr	Parameters	Value
1.	Project (*)	Grower -TWW for Agriculture –Irrigation, STP CADA Shahabad, Haryana.
2.	Capacity of STP	8-13 MLD
3.	Command Area	151 ha (373 ac)
4.	Design Discharge	2.4-3.6 cusec per 1000 ac.
5.	Crop	Wheat
6.	Blending	Blending water – Canal & TWW (50:50)
7.	Irrigation time	8 to 14 hours depending on crop water requirement and agro-climatic conditions.
8.	Irrigation type	Micro Irrigation & Furrow Irrigation System.
9.	Area (*)	5 acre
10.	Yield (*)	18 Quintal per acre
11.	Total yield	90 Quintal.
12.	MSP (*)	USD 25 per Quintal. *(Exchange rate-1 $ = Rs. 75, year 2019)*
13.	Total Income	USD 2,250
14.	Farm Expenses (*)	USD 1,200
15.	Net Income	USD 1,059
16.	BC Ratio	1.87
17.	Quality/Smell	The quality of wheat is the same as regular wheat and no bad smell / odor.
(*Because of Covid19 pandemic & Lockdown, could collect limited information & presented the above table after interaction and interpretation with various farmers over phone.)		

9.0 Conclusion

The physical quality of the product is the same as regular quality and has no bad smell/odor. It is just the mindset of people which needs to be changed. Government should encourage growers to use TWW for agriculture by providing incentives or subsidies.

However, private companies and growers should come forward to use blended TWW & fresh water supplies in ratio 50 : 50 to increase the productivity

Photo 1. TWW tank, Irrigation Control Head Unit

Photo 2. Drip Irrigation Wheat

photo 3. Furrow Irrigation Vegies

Photo 4.Sprinkler Irrigation -Germination

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A PRELIMINARY STUDY ON DRAINAGE EFFECTIVENESS OF A DISCONTINUOUS IMPROVED SUBSURFACE DRAINAGE

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ABSTRACT

A discontinuous improved subsurface drainage which can control surface and subsurface waterlogging had been proposed. The drainage performance and environmental influence have been studied. The drainage discharge, groundwater table and the drainage water quality of pH value, total nitrogen, total phosphorus, ammonia nitrogen, nitrate nitrogen, soluble phosphorus concentration under discontinuous improved subsurface drainage and conventional subsurface drainage have been measured based on field experiment. The results showed that the drainage performance of discontinuous improved subsurface drainage is significantly better than that of conventional subsurface drainage. In the test, the cumulate discharge of discontinuous improved subsurface drainage is about 2 times of conventional ones under one-time rainfall. Furthermore, through the short-term drainage process, it is found that the discontinuous improved subsurface drainage is more significant when surface ponding and heavy rainfall in short-time happen. Compared with conventional subsurface drainage, the discontinuous improved subsurface drainage can increase 23% of groundwater table descends, reduce 52% of ammonia nitrogen concentration and 2% of total phosphorus concentration and 7% of soluble phosphorus concentration, while increase 7% of total nitrogen and nitrate nitrogen concentration in average. The proposed discontinuous improved subsurface drainage has a great drainage performance on controlling surface and subsurface waterlogging. The study is helpful to solve the problem of surface and subsurface waterlogging in South China, and is better to improve the water environment of farmland.

Keywords: discontinuous improved subsurface drainage; conventional subsurface pipe drainage; discharge; drainage water quality

1. Introduction

China is the most populous country in the world, with a total population of 1.412 billion by the end of 2020. There is an urgent need for food and high-yield agriculture. It is well known that high-yield agriculture is based on well-drained land in most of the countries in the world [1]. The ratio of drainage area to irrigated area is generally high in countries with more developed agriculture. The ratio in the United States, Canada, Australia, Germany, France, and Japan is 2.0, 9.0, 1.0, 7.7, 1.15, and 1.05 respectively. While the ratio in China is only 0.32 [2]. Although the drainage area of each country can be affected by climatic conditions, there is no doubt that the current development of irrigation and drainage is not balanced in China with less investment in farmland drainage system [3]. Therefore, the farmland drainage has great potential and urgency for development in China.

New demands on farmland drainage methods have been put forward on account of the limited arable land resources. In many farmlands, it often happens that open ditches of drainage, especially field ditches, are filled and plowed by farmers due to the weak awareness of farmers about agricultural drainage and the desire for arable land [4-5]. As a result, the water in the fields cannot be drained out when floods or rainy seasons occur, which will cause crop yield reduction, especially in southern China. These problems can be actively avoided if subsurface drainage is used to replace the end-stage open ditch. It is also in line with the principle of changing the protection of arable land from single quantity management to trinity management of quantity, quality and ecology at this stage in China [6]. It showed that subsurface drainage, which occupies less arable land, has greater advantages among farmland drainage methods. The capacity of subsurface drainage to remove waterlogging is still small due to the influence of soil infiltration. To address this problem, an improved subsurface drainage technology had been proposed by Tao Yuan et al [7-9]. The drainage capacity and nitrogen and phosphorus discharge characteristics of the improved subsurface drainage technology had also been analyzed. The drainage flow can be improved if the whole subsurface pipe is used to lay a large range of sand and gravel materials (filter). While in this case a large amount of filter material would be consumed, which may lead to high cost.

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The water environment impact of farmland drainage, which is the main route of agricultural non-point source pollution into water bodies, should also be considered in order to meet the needs of the times. In this paper, the discontinuous improved subsurface drainage technology (hereinafter referred to as discontinuous improved subsurface drainage) is proposed. Based on the field test analysis, the efficiency of discontinuous improved subsurface drainage as well as nitrogen and phosphorus discharge characteristics are analyzed and discussed considering secondary drainage and short-term drainage processes. The research results can provide technical support for the development of farmland drainage theory and technology, and also provide reference for agricultural non-point source pollution management.

2. Discontinuous Improved Subsurface Drainage

Considering the problem of both surface and subsurface waterlogging, discontinuous improved subsurface drainage is proposed in combination with shaft and subsurface drainage. The discontinuous improved subsurface drainage is composed of a conventional subsurface pipe, a square block (or cylindrical) sand and gravel filter (or filter with anti-siltation capacity) that goes through the surface. It is recommended that the filter should be arranged in layers. The size of the sand and gravel filler (filter) can be selected according to the demand of drainage capacity. It is preliminarily suggested that the width of the vertical subsurface pipe is 20~400 cm, and the length along the subsurface pipe is 20~400 cm. The distance between the field blocks can be set according to the actual demand, which can be 2~200 m (Figure 1). Both surface ponding and groundwater can enter the pipe through the filter, which has the ability to quickly drain the water through the surface. At the same time, there will be no impact on farming since the upper part of the filter is fine sand and covers a small area. In addition, debris such as crop straws and larger particles of the soil will be filtered out when the surface ponding water passes through the filter, which effectively preventing the subsurface pipe from blocking.

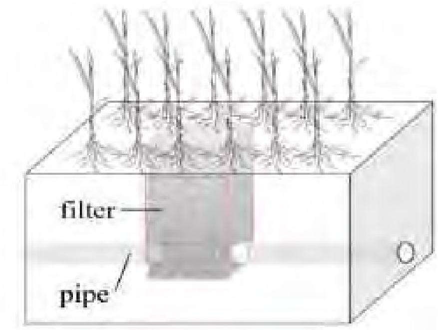


Figure 1 Structure of the discontinuous improved subsurface drainage

3. Materials and Methods

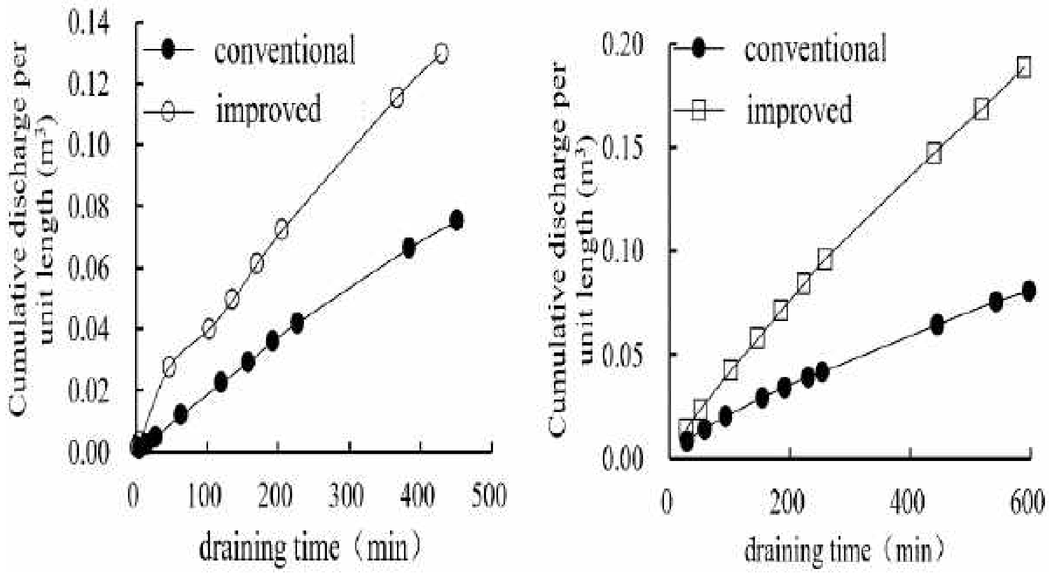
The field experiment was carried out in Lixin County (116°11′ E, 33°14′ N), which located in Huabei Plain of Anhui Province, China. The plots of discontinuous improved subsurface drainage and conventional subsurface drainage had been set up respectively. In order to prevent the interaction of water flow between different test schemes, three subsurface pipes were laid in each test plot with the drain spacing of 20 m and the length of 30 m. Perforated corrugated plastic pipes were used as the subsurface pipes with the diameter of 90 mm. The main task of local farmland drainage is to remove waterlogging and lower the groundwater table, and the crop is mainly rain-fed crop. In consequence, the average drain depth is 0.8 m under the condition of meeting the design requirements for groundwater table control. The width in the vertical direction of the subsurface pipe and the length along the subsurface pipe direction of the sand and gravel filling block are 180 cm and 130 cm respectively in the plots of the discontinuous improved subsurface drainage. One filling block is set in the middle of the 30 m long subsurface pipe, that is, the spacing between the filling blocks is 15 m. The outlet of all subsurface pipes shall be drained into the observation ditch for measurement. Two drainage tests were conducted on July 15 and July 19 in 2020 respectively. The drainage discharge was monitored and the water quality of the second drainage was tested with the sampling time being the beginning and middle of the drain process. The middle sampling time was about 4 h after the beginning. Parameters such as total nitrogen, total phosphorus, ammonia nitrogen, nitrate nitrogen, and soluble phosphorus concentration were measured. Additionally, two drainage process were monitored in 2021, including the drainage test of the cumulative rainfall of 88 mm from July 15 to 19 and 159 mm of heavy rainfall on July 28.

4. Results and Analysis

4.1 Drainage discharge

(1) Sub-drainage

The drainage process of discontinuous improved subsurface drainage and conventional subsurface drainage has been shown in Figure 2. It showed that the drainage performance of discontinuous improved subsurface drainage is better than that of conventional subsurface drainage. The discharge of discontinuous improved subsurface drainage is about twice of conventional subsurface drainage during the test period on July 15, 2020. And the effect was more significant at the initial stage of drainage. The cumulate drainage of discontinuous improved subsurface drainage is about 2.3 times of conventional subsurface drainage on July 19, 2020.



（a）July 15, 2021 （b）July 19, 2021

Figure 2 The cumulate discharge of discontinuous improved subsurface drainage and conventional subsurface drainage in 2020

(2) The drainage process

The cumulate discharges had been shown in Figure 3. The rainfall were 42.6 mm and 33.6 mm on July 15 and 16, 2021, respectively. The drainage discharge was smaller on July 15 due to the large groundwater depth and dry soil at the beginning of the rainfall. Therefore the discharge of discontinuous improved subsurface drainage was increased by only 6% compared with conventional subsurface drainage at this time. The effect of discontinuous improved subsurface drainage was more obvious with the increasing of rainfall infiltration into the soil.

The discharges of discontinuous improved subsurface drainage increased 34% and 42% than that of conventional ones on July 16 and July 17 respectively. After that, the effect of discontinuous improved subsurface drainage was weakened compared with that on July 17. The increase percentage of discharge was also 34% on July 18. Consistent with this drainage process, the effect of discontinuous improved subsurface drainage was more significant on July 28, with the discharge being 1.35 times of the conventional subsurface drainage ones. Due to the heavy rainfall on July 28, the groundwater table rose to the surface.

Then the discharge was 2.07 times of that of the conventional subsurface drainage on July 29. While the discharge was increased by 55% compared with the conventional subsurface drainage on July 30. It showed that the effect of discontinuous improved subsurface drainage is more significant when surface ponding and heavy rainfall in short-time happen. In the case of large groundwater depth, the discharge was increased when surface ponding and heavy rainfall in short-time happen. While the drainage effect is less than that of shallow groundwater depth.

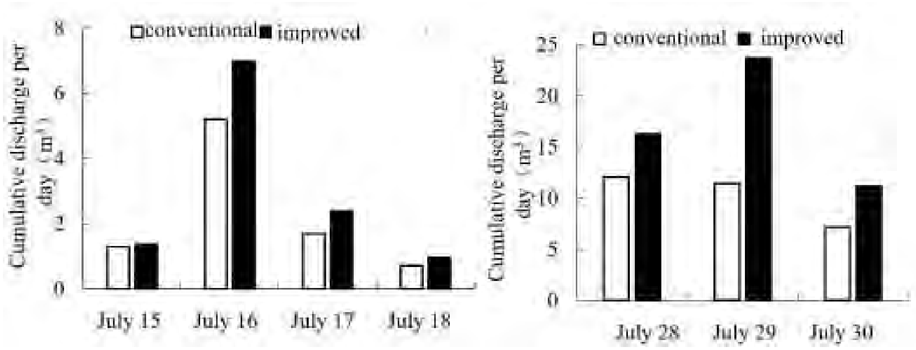


Figure 3 The cumulate discharge of discontinuous improved subsurface drainage and conventiona l subsurface drainage in 2021

4.2 Groundwater table

There was a small difference in groundwater depth between the plots of discontinuous improved subsurface drainage and conventional subsurface drainage when the experiment was started on July 15, 2020. Thus the variation of groundwater depth of this drainage was analyzed, as shown in Figure 4. Groundwater depth under conventional subsurface drainage was reduced by 7.7 cm. While groundwater depth under discontinuous improved subsurface drainage was reduced by 9.5 cm, which is 23% higher than that of conventional ones. It showed that the effect of discontinuous improved subsurface drainage to lower the groundwater table is more obvious.

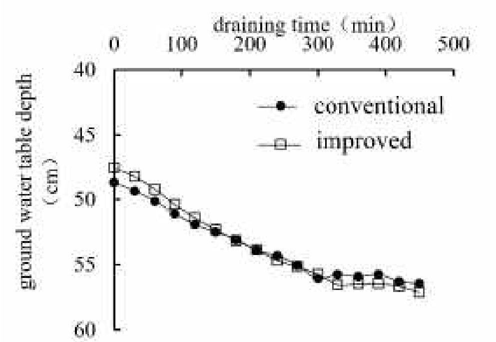


Figure 4 Groundwater depth of discontinuous improved subsurface drainage and conventional subsurface drainage

4.3 Drainage water quality

The drainage water qualities of pH value, total nitrogen, total phosphorus, ammonia nitrogen, nitrate nitrogen, and soluble phosphorus concentration in the early and middle drain stages of discontinuous improved subsurface drainage and conventional subsurface drainage had been shown in Figure 5. The pH values of the two types of subsurface drainage varied from 7 to 7.6 with no obvious acidity or alkalinity. And they both met the environmental quality standards for surface water in China. The ammonia nitrogen concentration of discontinuous improved subsurface drainage was reduced by 52% on average compared with conventional subsurface drainage. The reason is probably that the permeability of the soil (especially near the filter) was increased under the discontinuous improved subsurface drainage. Then the nitrification of soil ammonium nitrogen was increased and the content of soil ammonium nitrogen was reduced. In consequence, the concentration of ammonia nitrogen in the drainage was reduced. For nitrate-nitrogen and total nitrogen, the concentration of discontinuous improved subsurface drainage was about 7% higher than conventional subsurface drainage. There are two reasons for this phenomenon. The one is the increase in soil nitrification reaction. The other is that more soil nitrate-nitrogen was drained out under large hydrodynamic action due to the increasing discharge for discontinuous improved subsurface drainage. For total phosphorus and soluble phosphorus, the concentration of total phosphorus was larger in discontinuous improved subsurface drainage at the initial stage of drainage. But the average value of the concentration was lower than that in conventional subsurface drainage. The concentration of total phosphorus and soluble phosphorus was decreased by 2% and 7% respectively. It showed that the corresponding conclusion is close to the effect of improved subsurface drainage with sand and gravel filter in the literature [10], which discontinuous improved subsurface drainage has a more important role in the reduction of ammonia nitrogen, total phosphorus and soluble phosphorus.

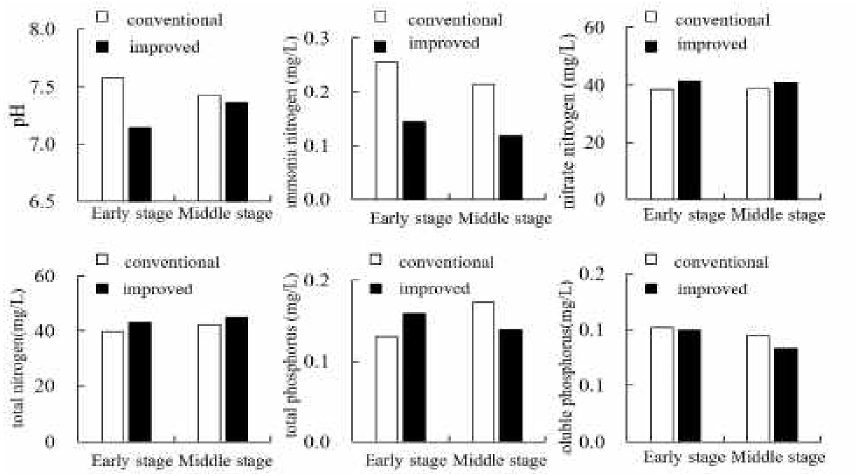


Figure 5 Drainage water quality indexes of discontinuous improved subsurface drainage and conventional subsurface drainage

5. Discussion

At present, there is no doubt about the ability of drainage can be increased in the discontinuous improved subsurface drainage. It has the characteristics of good ecological environment and economic feasibility. But its promotion and application should be on the basis of improving the capacity of farmland disaster prevention and alleviation. In terms of ecological environment, it had been found in this study that the emissions of ammonia nitrogen and phosphorus under discontinuous improved subsurface drainage can be effectively reduced compared with conventional subsurface drainage. But it had no effect on the reduction of nitrate nitrogen and total nitrogen in drainage. On the contrary, these two indexes had been increased to some extent. It is possible to continuously explore the filter with reduction for specific pollutants [11-13], especially the filter material with strong nitrate and nitrogen removal effect. It is also possible to use management tools such as controlled drainage and different layout methods for reasonable reduction [14-16], and to identify the migration and conversion mechanisms and main control factors of nitrogen and phosphorus elements in soil under the effect of drainage.

In terms of economic benefits, the volume of the filter of discontinuous improved subsurface drainage in the experiment is 39% less than that of the improved subsurface drainage in the literature [6], which means that the economic benefits will be significantly increased. That is to say, it is more economically feasible. Further studies are needed to determine how to set the size and spacing of the filter more rationally to facilitate drainage and reduce the impact on environmental.

6. Conclusions

In this paper, the discontinuous improved subsurface drainage technology had been proposed. Based on the field experiment, the drainage effect of discontinuous improved subsurface drainage was studied by comparation to conventional subsurface drainage. The drainage discharge, groundwater depth and water quality in drainage were preliminarily analyzed.

(1) In terms of the discharge, the drainage performance of discontinuous improved subsurface drainage is better than that of conventional subsurface drainage. The cumulate discharge of discontinuous improved subsurface drainage is about 2 times of conventional ones. The effect of discontinuous improved subsurface drainage is more significant when surface ponding and heavy rainfall in short-time happen. The increased percentage of its discharge is decreased as the groundwater level falls. At the same time, the effect of discontinuous improved subsurface drainage in lowering the groundwater table is more significant.

(2) In terms of drainage water quality, compared with the conventional subsurface drainage under the action of sub-drainage, discontinuous improved subsurface drainage has a better effect on the reduction of ammonia

nitrogen, total phosphorus and soluble phosphorus. In particular, the concentration of ammonia nitrogen can be reduced by 52%. But there is a small increase in nitrate nitrogen and total nitrogen concentration at the same time.

(3) In terms of drainage effect, discontinuous improved subsurface drainage has a good application prospect. It is more important to improve the drainage environment of farmland by accelerating the investigation of the more suitable filter. The study is helpful to solve the problem of surface and subsurface waterlogging in South China, and is better to improve the water environment of farmland.

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METHODOLOGICAL AND VISUAL JUSTIFICATIONS FOR THE MANAGEMENT, DESIGN AND OPERATION OF IRRIGATION SYSTEMS IN THE SOUTH OF RUSSIA

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ABSTRACT

Growing consumption of natural resources by humanity, including water, increasing climatic changes, require strengthening scientific research on the management and application of nature-saving ("gentle") technologies in the irrigation complex. Irrigation systems, being the infrastructure of landscapes, ensuring the development of agricultural production, would be permanently improved from generation to generation. The increasing load on water transportation systems for agriculture requires comprehensive control over the payment, quality and consumption of water. Discussion: the operating conditions of the Main Don Canal in the South of Russia (Rostov region), which has been functioning for more than 70 years and has a wear rate of about 70%, were studied. Feature reconstruction of the most dangerous sections of the Don Main Canal is proximity of the groundwater level to the earth's surface, which leads to the transition of free filtration to a propped one. The total losses on the 57-70 km section are -13.7□10 3 cubic meters per day, and in the presence of channel lining – 0.504 cubic meters. per day, which is 2.09 times less than with propped filtration in the earthen channel bed. For repairing the internal junctions of the bottom and slopes of irrigation channels by the concrete lining, it is advisable to use "galtels" which having a triangle form with sides: 10 – 50 mm, which avoids excessive consumption of repair material. Based on the consideration of bed channel culmination and specific filtration of water through concrete lining (0.112 sq. m. per day on the Don Main Canal), a methodology for assessing the water permeability of the anti-filtration concrete lining of irrigation canals has been developed. The research results are formilized in the Methodology and technological map for the restoration of the Don Main Canal (including using composite materials and polymers, bitumen-polymer mastic using one-, two-component latex emulsion). Using mathematical models and visualization tools, scenarios for automatically water distribution management, were developed. It's possible to predict water level in reservoirs and irrigation channels, restoration of biological resources and water quality using algolization technologies in order to avoid negative consequences in soil and crops. A functional model of interaction of elements of a convergent system of typical irrigation system design has been developed; 3D model of the processes occurring in the system "irrigation canal – agricultural field – soil – crop yield – profitability of production"; an algorithm for attracting investments and the order of reconstruction of irrigation canals has been elaborated (based on the above costs: current in agricultural production and operational for inter-farm network). Visualization and standard design of irrigation systems of a new generation are constrained by insufficient consideration of natural and anthropogenic factors, the underdevelopment of the international legislative and regulatory framework. Improving the methodology for the creation, operation and restoration of irrigation systems based on Russian experience and achievements will enrich the international practice.

Keywords: Reconstruction; irrigation equipment.

1. Introduction

The growing consumption of natural resources, including water, and the increasing climate changes require the strengthening in the field of generalization of accumulated knowledge, systematization, and presentation in digital formats. Irrigation systems, becoming the infrastructure of natural landscapes, ensuring the development of agricultural production, must be permanently improved, from "from one generation to other generation". The increasing load on water delivery systems for agricultural lands requires an integrated approach to the operation and repair of irrigation systems.

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The aim of this study is a methodological and visual justification of the management system, design, and restoration of main channels.

The object of this study is the Don Main Canal (DMK) with a length of 112 km, operating for more than 70 years, delivering water to the southern regions of Russia. The DMK consists of 5 head waterworks structures, several pumping stations, fish protection structures, a hydraulic tunnel, a base with repair and mechanical services.

2. Methods and material

The study consisted on economic and visual modeling, field observations on the Don Main Canal (author's - DMK) in the Rostov region. The empirical base of the research institutes of the Federal State Budgetary Institution VNIIOZ (Volgograd), the Federal State Budgetary Institution VNIIGiM named after A.M. Kostyakov (Moscow) was used. For combined linings of the main channel, the option of using geocomposite materials was considered. Combined cladding reduces the cost of the anti-filtration screen, increases outflow coefficient, and reduces construction time.

3. Discussion

The operating conditions of the Don main Canal, located in an earthen, partly in a lining channel, have been studied. The degree of wear about 70% has been observed on main part of channel (Figure 1).

Figure 1. Don Main Canal, Russia, 2022

A feature of the operation of the DMK is the high groundwater level close to the ground surface, which leads to the transformation of gravity filtration to a propped one. Total water losses in some areas reach - **$13{,}7 \cdot 10^{3}$** cubic meters per day, and in the other areas with channel lining – 0.504 cubic meters / day, which is 2.9 times less. The question of the use of galtels having a triangle form with sides: 10 – 50 mm was studied for repairing the internal junctions of the bottom and slopes of concrete lining of irrigation channels. The most effective types of linings are combined concrete with geocomposite materials, where the percentage of use of monolithic concrete as part of anti-filtration linings decline to 20 -30%. Concrete lining, as a rule, in recent years have been used only as protection (directly in the zone of wave impacts), to prevent erosion and deformation. Geomembrane have the following advantages: they are not subject to fouling and are easily repaired, since damage, even the smallest defect, can be detected and eliminated. For example, the Senhora Canal to Porto (Portugal) with a length of 2.5 km due to the formation of large cracks, increased roughness of the lining significantly reduced the water flow. Figure 2 shows a variant of the design of the DMK screen, made without a protective material on the bottom and part of the slope in the zone of wave and ice impact (Figure 2).

To facilitate the reconstruction of main channels, it is advisable to get access to electronic databases. Practice has shown that "Digital land reclamation" allows professional to quickly obtain information from their relational databases, and "Standard design solutions", which contain information about the types and main technical characteristics of waterworks, their structures, the required works, the cost of materials to design the reconstruction of the main channel. The database diagram in the structure of the information technology support complex for the design and reconstruction of main channels is shown in Figure 3.

Visualization and standard design of irrigation systems are constrained by insufficient information about natural conditions, the presence of anthropogenic factors, as well as the underdevelopment of the international legislative and regulatory framework. For modern designing irrigation channels, it is very important to have information about the sprinkling equipment would be placed on agricultural fields. Modern high-tech sprinkling machinery (SM) of the company "Bauer GmbH" (Austria) can automatically change the mode of water consumption from zero to several hundred liters per second, and this affect the operating modes of the water distribution system as a whole (Figure 4).

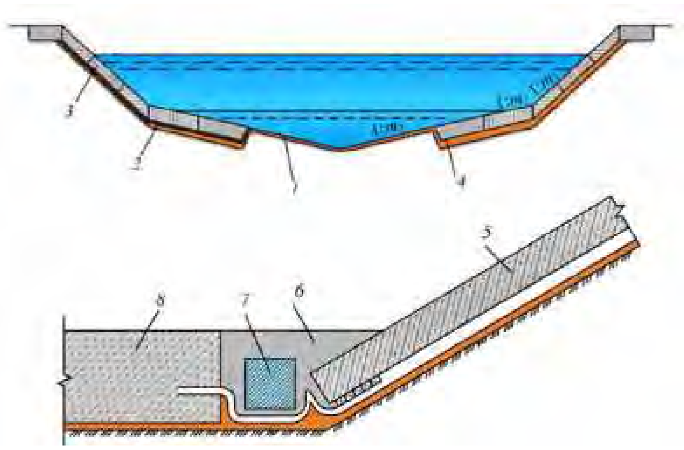

Figure 2. A variant of the lining of the main channel based on geocomposite materials

(1 – geocomposite material combined with geomembrane; 2 – polyethylene geomembrane; 3 – prefabricated slabs; 4 – joint seam; 5 – polyethylene geomembrane; 6 – cement mortar; 7 –concrete cubes; 8 – monolithic concrete)

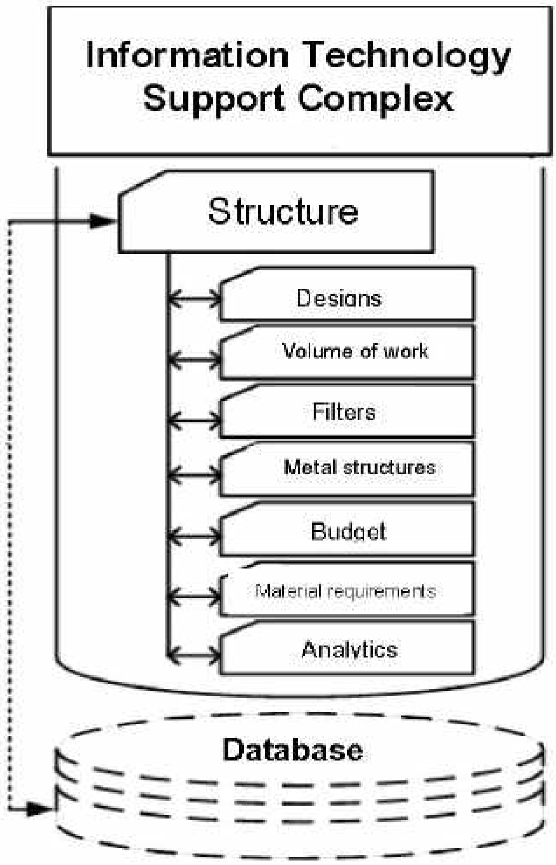

Figure 3. Database of standard design solutions in land reclamation design.

Figure 4. Water intake from the canal at the Linestar installation, sprinkling of fields with the Centerliner installation (with a circular type of movement) of the company "Bauer GmbH "(Austria).

In modern SM with the Zone Control function (programmable opening/closing of sprinklers), the water consumption is not determined by the maximum performance of its water intake unit $Q_{\text{дм, max}}$, but the sum of the amount of expenses of open sprinklers, which is determined by the formula:

$$Q_{\text{дм},i} = \sum_{j=1}^{n} q_j \quad , (1)$$

where $Q_{\text{дм}, i}$ – actual consumption taken by the SM from the sprinkler in the 1st position, l/s;

i – position number of the sprinkler machine on the irrigator;

n – number of simultaneously operating sprinklers, pieces;

q – consumption of the working of the device, l/s.

Automation of the water distribution control system allows to observe the calculated flow rate in the sprinkler $Q_{\text{ор, расч}}$, which provides maximum performance SM $Q_{\text{дм, max}}$, lower water consumption $Q_{\text{дм}, i}$ (Figure 5).

4. Conclusions

The intensive use of scientific and technical achievements in the field of land reclamation determine the need to develop standard design decision as part of modern means of information technology support. Systematization of all available information, its structuring in the form of electronic databases, allows speeding up the work on the management and reconstruction of irrigation main channels. The methodology developed by Russian scientists for assessing the water permeability of the anti-filtration concrete lining of irrigation canals and the technological map of the restoration of the Don Main Canal using composite materials, bitumen-polymer mastic have allowed expanding the scientific potential of the world reclamation science. With the help of neural networks and visualization tools, it is possible to develop scenarios for automated water distribution management on main channels, taking into account sprinkler machines. To reduce water losses on the main channels, the use of anti-filtration coatings is required, especially on the ground areas of the base with a filtration coefficient of more than 0.20 m / day. Studies on the Don Main Canal in Southern Russia have shown that the use of anti-filtration protection reduces water losses by 2.09 times, and total losses by 6.55×10^3 times.

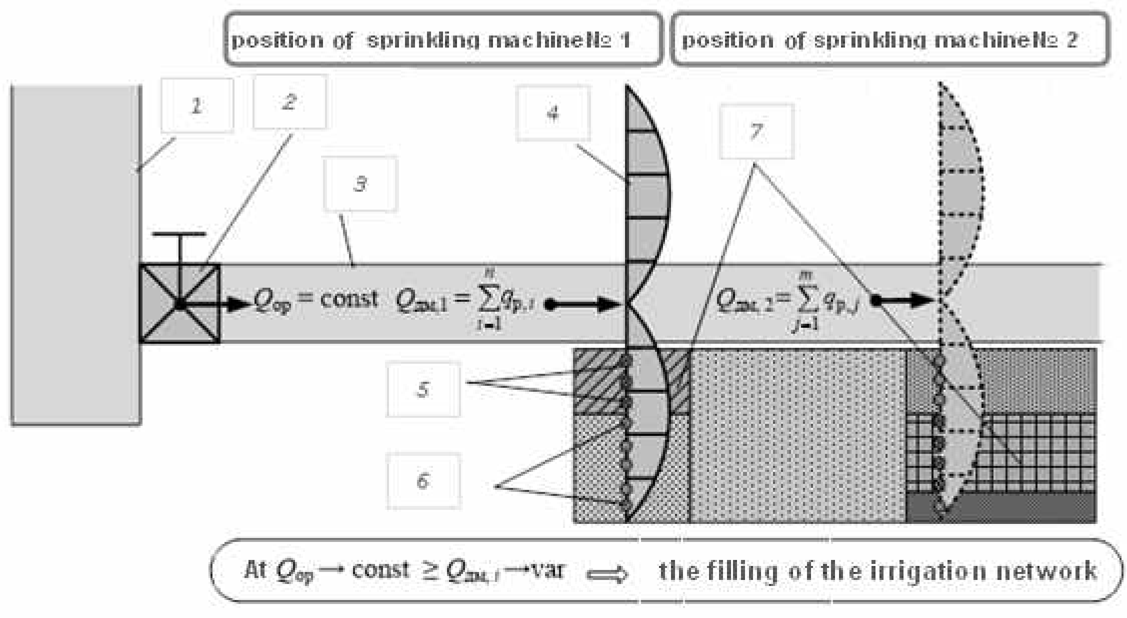

Figure 5. Scheme of interaction of the open water distribution network with the Center-liner front-type sprinkling machine of the company "Bauer GmbH "(Austria)

(*1* – distribution channel; *2* – the connection point of the irrigation network to the main canal; *3* – irrigator; *4* – sprinkling machine; *5* – non-working sprinklers; *6* – working sprinklers; 7 – zones with controlled water supply)

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Question 64: What alternative water resources could be tapped for irrigated agriculture?

Quelles ressources alternatives en eau pourraient être exploitées pour l'agriculture irriguée?

Question 65: Which on-farm techniques can increase water productivity?

Quelles techniques agricoles peuvent augmenter la productivité de l'eau?

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