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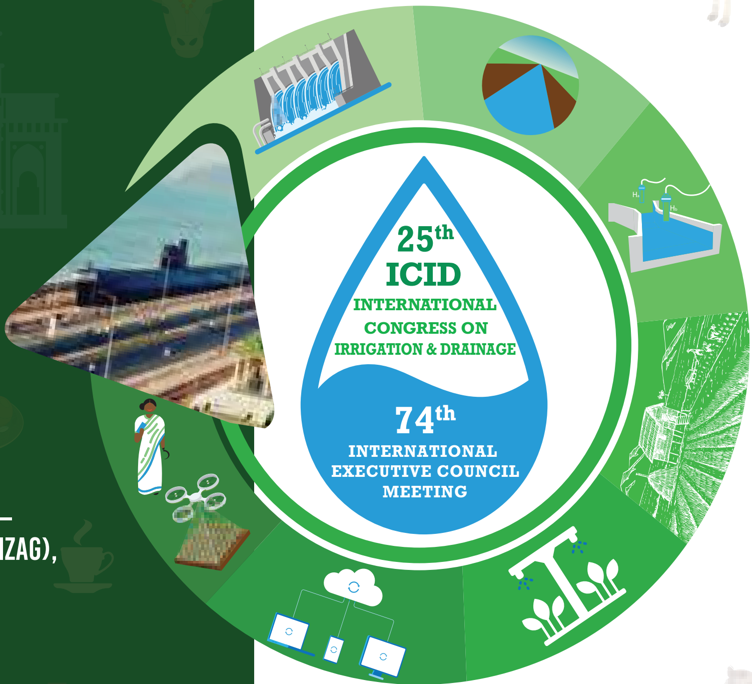
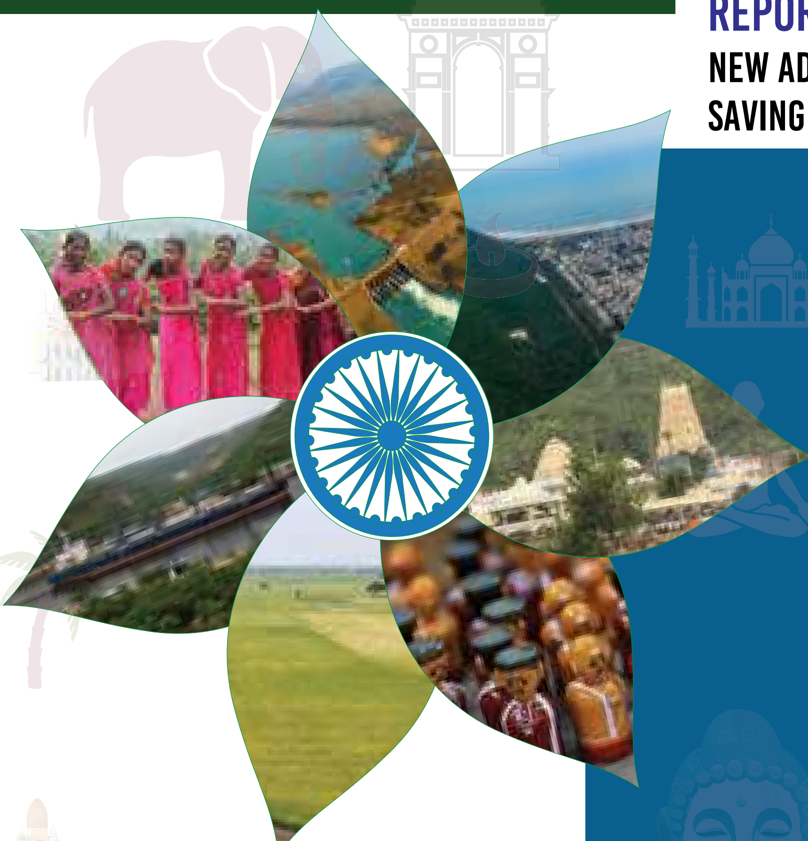
25TH ICID INTERNATIONAL CONGRESS ON IRRIGATION AND DRAINAGE

1-8 NOVEMBER 2023, VISAKHAPATNAM (VIZAG), ANDHRA PRADESH, INDIA



REPORT

NEW ADVANCES IN WATER SAVING IN IRRIGATION



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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Water secure World, free of poverty and hunger achieved through sustainable rural development.

MISSION

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- **A** Enable Higher Crop Productivity with Less Water and Energy
- **B** Be a Catalyst for a Change in Policies and Practices
- **C** Facilitate Exchange of Information, Knowledge and Technology
- **D** Enable Cross-Disciplinary and Inter-Sectoral Engagement
- **E** Encourage Research and Support Development of Tools to Extend Innovation into Field
- **F** Facilitate Capacity Development

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Report on New Advances in Water Saving in Irrigation

September 4, 2023

Activity Report by

Working Group on Water Food Energy Nexus (WG-WFE-N)

Technical Report of erstwhile WG-WATER & CROP

Prof. Dr Ragab Ragab
Chairman and President, ICID
Wallingford, UK

Presented at:

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Preface

Given the current population growth, accompanied by climate and land use changes, today most countries are facing unprecedented pressure on their water resources. The global population is growing fast, and the estimates show that, with current practices, the world will face a 50% shortfall between forecasted water demand and available water supply by 2050. Furthermore, chronic water scarcity, hydrological uncertainty, and extreme weather events (floods and droughts) are considered as some of the biggest threats to the global prosperity, stability, and food security. The most common misconception is that people believe water is replenishable and will be around us forever. History tells us that hundreds of rivers ran dry and some disappeared. This highlights another misconception about the use of word sustainability <**https://rb.gy/an7k9**>.

In the minds of some people, sustainability is not time dependant, but the truth is that it is. As water resources are rainfall, and rainfall varies temporally and spatially with varying frequencies and intensity, no one is guaranteed to receive the same amount at the same place and the at the same time. Therefore, practically, there is no sustainable water resource but there is sustainable management of the resource by using it efficiently to last longer for an intended period. Sub-Saharan Africa, thousands of years ago, was under the rainy geological era, while Europe was under the Ice Age era. Now, the aquifers under the African deserts of Egypt, Libya, Chad, Sudan, etc. that were filled up during that rainy era are not renewable any more under the reduced or no rainfall at present.

To narrow the gap between water demand and water availability, proper water management is necessary. Most of the rainwater is wasted even though it is one of the most precious natural resources. In fact, historically, humans had developed some techniques to conserve the available water resources by building small bunds, water tanks, check dams, for water harvesting and storing rainwater for food production. Large dams are now the most common structures, and they are on the increase. However, dams have some issues related to safety and impact on communities and environment: **<https://rb.gy/kklto>.**

Water authorities and farmers can play an important role in water conservation by using suitable techniques, like rainwater harvesting. Authorities should allow farmers to harvest rainfall-runoff water during river high flows and store the water for dry /low flow periods.

Ministries of agriculture should also provide farmers with the recommendation on the most efficient water use crops, best crop rotation, most drought tolerant crops, most heatwave tolerant crops, etc. Irrigation authorities should advise farmers on the exact crop water requirement, how much water to apply and when to irrigate **<https://icid-ciid.org/icid_data_web/2wasag_ragab.pdf>, & <https://rb.gy/tft12>.**

Authorities should also advise on the most efficient irrigation systems to use, provide loans to farmers to adopt new efficient irrigation systems, such as subsurface drip, Ultra Low (pressure and energy) Drip Irrigation (ULDI), Variable Rate Irrigation (VRI), Centre Pivot systems, and Nano (semi-permeable tape) Irrigation, to provide automated irrigation networks. The policy should also aim at increasing the water productivity within the Water-Energy-Food Nexus < **https://rb.gy/9ttgd >** so that we produce "more crop per drop per kilowatt per unit of land". In addition, we need to modernize the irrigation sector to be fully automated and equipped with sensors and minimize losses by seepage, leakage, and evaporation **<https://rb.gy/ktbhv>.**

Also, to narrow the gap between water demand and supply, we need to use non-conventional water resources such as treated waste water, brackish saline water, drainage water, agro-industry waste water, fish farms waste water etc. for irrigation.

Given irrigation globally consumes around 70% of the available fresh water resources, it is vital to use this water more efficiently as population is growing while water resources quantity stays nearly the same. We are expected to double food production to feed 9.8 billion people by 2050 from the same limited amount of water we have now. We will need to increase water supply, increase water use efficiency, and water productivity, using less water consuming crops and more. One of the most water consuming crop in the world is Rice. This report contains several approaches on how to use less water to grow rice and achieve good yield and save water. The report also shows examples of new approaches for cultivating rice including "dry rice", different land preparations, and different high yielding varieties, different irrigation systems and management. Examples of new approaches of water saving in rice cultivation are given for Egypt, Italy, Japan, and India.

Models can be useful management tools. In recent years, models attracted more attention and once calibrated and validated using field observations, they were used as management tools for estimation crop water requirements, expected yield under different irrigation systems, when using different water qualities and different land and fertilizers managements. SALTMED is an example of such management models. The model has been developed over four European Commission funded projects (SALTMED, SWUP-Med, SAFIR and Water4Crops) and tested using field observations over a number of years (Ragab et al., 2005a&b, Ragab et al., 2015, Ragab 2020). The SALTMED model simulates the crop growth and dry matter, water and solute movement under various irrigation systems (surface and sub-surface) and under full and deficit irrigation including the Partial Root Drying Method, PRD. The model also simulates drainage flow to open and tile drains, shallow water table height, Nitrogen cycle, and estimates the actual and potential Evapotranspiration as well as the water use efficiency and crop water productivity.

SALTMED model can simulate up to twenty fields or treatments simultaneously. The model also simulates crop rotations. The model has been tested against a number of field experiments in different countries such as: tomato and potato under drip irrigation in Syria, Egypt, Crete, Serbia and Italy (Ragab et al., 2005b and 2015, Afzal et al., 2016), in Iran, sugar cane under sprinkler irrigation (Golabi et al., 2009), in Greece, cotton under drip irrigation (Kalfountzos et al., 2009), in Denmark, quinoa irrigated with saline water (Razzaghi et al., 2011), in Morocco, quinoa, sweetcorn and chickpea under drip irrigation (Hirich et al., 2012), in Brazil, vegetable crops (Montenegro et al., 2010), in Italy, quinoa and amaranth using saline water (Pulvento et al., 2013a &Pulvento et al., 2015b), in Portugal, rainfed and irrigated chickpea (Silva et al., 2013), in Morocco, quinoa under deficit drip irrigation (Fghire et al., 2015), in Turkey, sweet pepper in green houses using saline water (Rameshwaran et al., 2015, 2016b), in Syria, legumes (lentil, chickpea and faba bean) using saline water (Arslan et al., 2016, Rameshwaran et al., 2016a), in Turkey, quinoa using fresh and saline water (Kaya and Yazar, 2016) and in Egypt, potato using gated pipes furrow irrigation (El-Shafie et al., 2017).

The abovementioned studies illustrated the capability and reliability of the SALTMED model in simulating the filed observed yield and dry matter, soil moisture and salinity concentration of the root zone. In addition, the model was also able to derive an important relation commonly known as the salinity-yield response function (Arslan, 2016; Rameshwaran et al., 2015, 2016a, 2016b). SALTMED was also used to study the possible impact of climate change on yield, dry matter, crop water requirements, harvest and sowing dates, and length of the growing season of amaranth and corn crops in Italy and Morocco (Pulvento et al., 2015a; Hirich et al., 2016). The model has been intensively used in Egypt on a variety of field crops (Abdelraouf and Ragab 2017, 2018a,b,c, Abdelraouf et al., 2020, Dewedar et al., 2021, Marwa et al., 2020, El-Shafie et al., 2017), in Pakistan (Chauhdary et al., 2019, 2020), in Iran (Basiri et al. 2020, Dastranj et al., 2018), in Portugal (Siva et al., 2013, 2017) and in Morocco (Hirich et al., 2012, 2016 and 2020, Filali et al., 2017, Fghire et al., 2015, 2017).

The model has also been used to derive some parameters that are not easy to measure (e.g. Leaf Area Index, LAI, Salinity tolerance index π50, etc.) More details about the applications are published in a Special Issue of Journal of Irrigation and Drainage (Ragab 2020). The model is available at ICID website **https://icid-ciid.org/inner_page/41** and this report gives detailed instruction on how to install, run and get the results.

We all have the responsibility to save water. We need to adopt water saving approaches, Saving Water-Saving Live <https://www.youtube.com/watch?v=STWrY68zpIY>.

Finally, I would like to acknowledge the help of Dr Nadine Depre (my wife) in revising and editing the different contributions of the report. In addition, I would like to express my sincere appreciation and gratitude to the ICID Central Office for their efforts and cooperation during the course of the Technical Report of the erstwhile WG-WATER & CROP.

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FUTURE OF RICE FARMING WITH DRIP IRRIGATION AND FERTIGATION TECHNOLOGY FOR HIGHER WATER PRODUCTIVITY

Dr. P. Soman[1]

ABSTRACT

Rice is known for consuming very high volumes of Irrigation water in the conventional cultivation with flooding the rice field as the method of irrigation. Studies were conducted, first in the research farm and then in several farmers' fields where drip method of irrigation and fertigation was applied to rice cultivation. The results were positive and showed that, 1. Rice can very well be grown with soil wetting alone without flooding the field, and 2. With drip irrigation, the grain yield was higher (10-22%) than with the conventional irrigation method. The water consumption was also reduced. Hence the water productivity of irrigated rice increased. The paper covers results obtained from farmers' fields. It also narrates the challenges in extension of the technology.

Key words: Rice, Drip irrigation, Fertigation, Water productivity.

1. Introduction

Approximately 80 % of fresh water is used for irrigation of agricultural crops in India. Thirty percent of irrigation water is used for cultivation of rice under conventional lowland rice system. On average, rice uses 1400 liter water by evaporation and transpiration to produce one kg rice (Bas Bouman, 2009). Exploitation of surface and ground water has reached its maximum in many States so that, unless water saving technologies are used, it will be impossible to practice, sustainable agriculture in coming years.

The demand for water for domestic, municipal, industrial and environmental purposes will rise in the future, and less and less water would be available for irrigation. Water availability for agriculture in India which is 83.3% of total water used today, will shrink to 71.6% by 2025 and to 64.6% in 2050. We are almost exhausting all of the irrigation water to increase any more land under irrigation.

Rice is the main grain that is in demand in India and South Asian countries. A hectare of rice, in conventional puddle cultivation, uses 1300-1600 mm water per season (13 to 16 million liter) as per the Ministry of Agriculture, government of India. (But in reality farmers use much more water (up to 2000 mm) in many delta areas in India. In Asia, 17 million ha of irrigated rice will face "physical water scarcity" and 22 million ha may have "economic water scarcity" by 2025. The highest share of this inadequacy will occur in India, the largest rice producer of the region.

The future of rice production which consumes a lion's share of water (85%) used in irrigated agriculture will therefore depend heavily on developing and adopting technologies and practices which will use less water with highest use efficiency. Rice is cultivated usually in a puddle condition with large volumes of water and grown in standing water. The water productivity is hardly 0.15 kg/m^3 water, which is very low.

With all that water use, still the rice yields in India are not very high and seems to have stagnated (Figure 1) in the last decade or so.

At Jain Irrigation systems whose motto is "more crop per drop' extensive field trials were carried out using drip irrigation and fertigation technology on important economic crops including water "guzzlers" such as banana, sugarcane and rice and found that the water requirement of these crops has been reduced to 40-50 % using micro irrigation system; under this system moisture availability in soil is kept close to crop water requirement and the performance of crops are optimal, increased yields and improvement in quality of the produce could be achieved. Realizing that more than 90 % of rice is produced under inundated lowland system, extensive field trials were carried out since 2007, several rice varieties and genotypes under upland aerobic and low land transplanted conditions in farmers' field using drip system to maximize yield and water productivity.

[1] Senior Vice President and Chief Agronomist, Jain Irrigation Systems Ltd, Maharashtra.

Indian average productivity of rice is very low (Figure 1). Farmers use excess water and produce less!

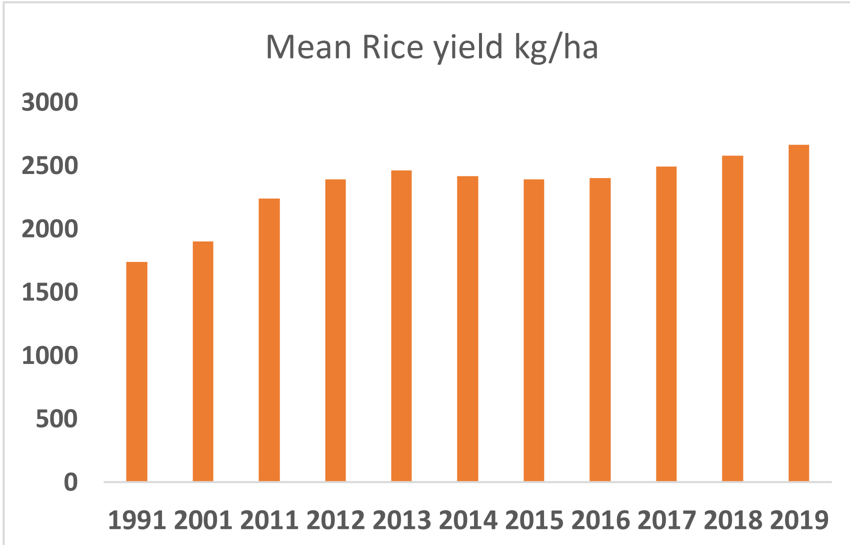

Figure 1 Average rice yield in India under conventional water management systems (Statista)

In the case of several other so called high-water-user crops - sugarcane, banana, vegetables, etc. it was found that the actual water need is 50 -60% lower than what was thought. This is made possible by drip irrigation technology; moisture availability in soil is kept close to the crop water requirement on a continuous basis. In this method, the crop performs close to its genetic potential and yields are enhanced. Given that 45 per cent of the country's total irrigation water is used solely for rice cultivation, the need to improve farming methods is imperative.

Besides being wasteful, excessive use of water results in lower yields and adverse environmental effects such as soil salinity and waterlogging. Paddy yields in irrigated regions of Tamil Nadu, Punjab and Haryana range from five to six t/ha, whereas in the high-rainfall areas of eastern Uttar Pradesh, Bihar, West Bengal and Orissa, the yields are about 1.8 t/ha. The main reasons for the poor yields are improper irrigation management and waterlogging. Economic analysis of this issue is reported by Asok Gulati and Gayathri Mohan (2018). Their study brought out the non-uniformity in rice water consumption across Indian States. Farmers in Punjab consumed twice the amount of water to produce a unit of rice compared to farmers in West Bengal and Bihar.

The drip technology is tested and found suitable in both the traditional wet rice and the dry seeded rice (DSR). Dry seeding is practiced in aerobic rice cultivation; and it is similar to what is generally referred to as upland rice (topographically high altitude).

This article mainly discusses both the experimental trials, and farmer demonstrations in an effort to commercialize a package of technology for growing rice with optimum water economy.

2. Experimental stage

Research trials were conducted by establishing drip irrigation systems in several rice ecosystems spread in many States in India- Andhra Pradesh, Maharashtra, Rajasthan, Uttar Pradesh, and Tamil Nadu. Trials were also conducted in the two major crop seasons, rainy (Kharif/autumn) and Post-rainy (Rabi/spring) and in summer. Trials with drip irrigation and fertigation were conducted in both dry seeded rice (DSR) and in transplanted rice methods of cultivation.

Varieties used: Hybrids used are Arize 6129(Bayer), RH 257(Monsanto), MK 2325(Syngenta), duration of crop after sowing is 115 to 140 days. Other varieties released by PAU like PR 111, PR 113, PR 114, PR 115 and PR 120 are used, duration of crop after sowing is 130 to 145 days.

In Basmati varieties used are Basmati 370, Basmati 386, Super Basmati, Pusa Basmati 1121; duration of crop 130 to 150 days. Additionally, other local prominent varieties were also included in each location.

2.1 *Agronomy practices standardized during the trials.*

1. Prepare well leveled and pulverized soil with adequate moisture. (Do a pre planting plough, irrigate and plough again before land is ready for rice planting).
2. Prepare Bed and furrow if possible.
3. Hand sow / drill the seeds.
4. Plant at a spacing of 20 x 15 cm (ROW –ROW x PLANT –PLANT)
5. Depth of seed 2 cm in dry seeded cultivation.
6. Fully drip Irrigate the field after sowing to provide the required moisture.
7. Drill the basal dose using a drill or apply on the bed before planting and incorporate.
8. Weed control: In the absence of standing water heavy weed infestation was envisaged. However, weeds could be easily controlled by a combination of hand weeding and rice husk mulching or by weedicide application. Application of Pendimethalin at 500ml/acre at 72 hours after sowing provided effective control.
9. Routine observation for insects (Stem borer, Leaf roller) and disease incidence were made during the crop growing season.
10. Irrigation in drip plot was done by placing two drip lines on each bed (Jain inline drip laterals 16 mm diameter with drippers of 4 liter per hour placed at 50 cm spacing along the drip line).
11. Fertilizers were injected (fertigation) through a ventury system following a schedule that was prepared for each location.

The amount of irrigation varied from location to location based on the evaporation at the location (Table 1) The fertilizer doses are varied based on the fertilizer recommendations prevailing in each location (Tables 2 & 3).

Table 1. Irrigation schedule for Drip irrigation$

Serial No.	Period	Mean Daily Evaporation (mm/day)	Crop Water Requirement (l/ha/day)
1	June 1 fortnight	5.53	12289
2	June 2 fortnight	5.53	55300
3	July 1 fortnight	5.42	60222
4	July 2 fortnight	5.35	59444
5	Aug 1 fortnight	5.23	69733
6	Aug 2 fortnight	4.91	65466
7	Sept 1 fortnight	4.87	54111

This table (used for Andhra Pradesh for June planting, Kharif) is an example of the different schedules followed in different locations mentioned in the paper.

Table 2. Fertilizer recommendations for each state (basis for fertigation schedules)

State of India	N kg/ha	P kg/ha	K kg/ha
Andhra Pradesh (& Telengana)	180	62.5	75
Chattisgarh	220	55	125
Maharashtra	100	50	50
Punjab	150	60	45
Tamil Nadu	150	50	50

Table 3. Ratios of N and K used to prepare the Fertigation schedule in each of the farmers' fields. (all P fertilizer is applied to the soil at planting).

*FERTIGATION SCHEDULE	
Stage of Crop	N: K ratio
till 10 DAP #	01:00
11-35 DAP	03:01
36-55 DAP	01:01
55-65 DAP	01:03
71-85 DAP	00:01

*All P fertilizer is applied as basal during field preparation along with FYM (manure), Zn, and Fe.
DAP = Days after germination in Direct seeded or plant establishment in Transplanted rice.

3. Rice yield, water and Energy use under drip irrigation

Drip irrigation enhanced rice yield by 22.5% and reduced water and Energy consumption by 66 and 52%, respectively (Table 4). The yield improvement occurred in all rice varieties tested (Table 5).

Table 4. Water and energy use under two different Irrigation methods (2009-2010) trial, Elayamuthur farm, (10o 34' 48'' N /77o 14' 24'' E), Coimbatore, Tamil Nadu (Rice variety, ADT 45)

Method	**Yield (ton/acre)**	**Water use (million litre/acre)**	**Energy Use (kWh/acre)**
Flood	3.1	9.5	467
Drip	3.8	3.2	226
Difference, %	22.5	66.3	52

(Soman et al., 2018a)

Table 5 Yield of different varieties under drip and conventional flood plots (harvested from Jalgaon, (21o 2' 54'' N/ 76o 32' 3'') Maharashtra.

Rice yield in a trial, Jalgaon, Maharashtra (ton/acre)		
Variety	**Flood irrigation**	**Drip irrigation**
SBH-999	2.4	3.2
25P25	1.8	2.7
25P31	2.8	3.2
MAS- 946-1	2.5	2.5
Try (R)-2	2.8	2.9
BPT	1.9	2.2
Pusa Sugandha	2.3	3.4

The field trials proved that: (1.) Keeping the soil wet alone and not providing standing water results in yields comparable or higher than in flooded (with standing water) condition.; (2.) Weeds, thought to be a major issue in non-flood situation can be managed by mulching the seedbed with rice husk at planting and one manual weeding or by minimum weedicide application; (3.) The performance of several varieties indicated that provision of soil moisture is the key requirement for rice production and not standing water.

4. Demonstrations in farmers' field

As a second step the drip irrigation technology for rice production was demonstrated in farmers' fields in many states during 2009- 2019 (Table 6). Irrigation systems were installed by the company and operated by farmers. Necessary training on operation and maintenance was given to the farmers. Irrigation and fertigation schedules were prepared by experts who advised the farmers. Rice yields were higher in drip than in the conventional irrigated plots in all locations and all varieties.

4.1 Benefits from drip irrigation in rice cultivation

Observations from the research plots and farmers' fields can be summarized as follows:

(i) Early and uniform maturity of the crop
(ii) Lesser labour use for cultivation
(iii) Lesser Cost of cultivation
(iv) Higher input use efficiency - Water and Fertilizer
(v) Higher yield
(vi) Less water consumption
(vii) Less pumping energy use
(viii) Lower ground and canopy humidity resulting in low incidence of pests
(ix) Lower rates of leaching and absence of run off resulting in lesser pollution by fertilizer and agrochemicals.
(x) Drip-Fertigated rice has been found to have good grain qualities.

The grain quality tests indicated the following attributes for rice produced by drip and fertigation instead of flood irrigation.

(i) Lower percent of chaff
(ii) Lower percent of broken grain

(iii) High millabililty

(iv) No perceptible shift in cooking time

(v) No perceptible change in taste of cooked rice

(vi) Lower levels of pesticide residue in the produce

(vii) Reduced methane emission from the fields

(viii) Reduced mosquito population due to lack of standing water.

(ix) Contributes to human health maintenance

Table 6. Drip for rice a summary of the performance in different farms

State	District	Area Under Drip (acre) [1ha= 2.5 acre]	No of Farmers	First Installation date	Crop Cycle (Rice + Rotation Crop)	Drip line space (m)	Yield change and water economics of rice crop
Andhra Pradesh	Visakhapatnam	0.36	1	2010	Rice	1	70% more yield and 55% less water use
	Visakhapatnam	9.13	7	2018	Rice-Maize Sesame	0.7	58% more yield and 55% less water use
	Kurnool	0.63	1	2013	Rice	1	60% more yield and 45% less water use
	E. Godavari	3	3	2013	Rice	0.6	35% more yield and 45% less water use
	W. Godavari	0.75	1	2013	Rice	1	28% more yield and 50% less water use
	Prakasam	2.5	2	2018	Rice	0.6	78% more yield and 45% less water use
	Vizhianagaram	1	1	2013	Rice – Vegetable	0.6	39% more yield and 55% less water use
Telengana	Medak	3	1	2009	Rice – Maize	0.6	58% more yield and 55% less water use
	Medak	0.75	1	2010	Rice	0.6	23% more yield and 45% less water use
	Medak	3.5	2	2018	Rice	0.6	67% more yield and 45% less water use
	Medchal	2	1	2018	Rice	0.6	47% more yield and 55% less water use
	Kareemnagar	1	1	2013	Rice	1	52% more yield and 55% less water use
	Nalgonda	2	1	2013	Rice – Musk melon	0.6	69.5% more yield and 50% less water use
	Warangal	1.5	1	2010	Rice	0.6	42.5% more yield and 50% less water use
Haryana	Ambala	11	11	2018	Rice-Wheat Rice Potato	0.6 and 0.75	10% - 18% more yield and 51% - 53% less water use
	Karnal	13	13	2018	Rice, Water Melon, Wheat	0.6 and 0.75	10% - 18% more yield and 51% - 53% less water use
	Kurukshetra	13	13	2018	Rice - Wheat	0.6 and 0.75	10% - 18% more yield and 51% - 53% less water use
Karnataka	Raichur	1	1	2013	Rice	1	41% more yield and 55% less water use
	Belgaum	1.5	1	2019	Rice	1.2	37.5% more yield and 40% less water use
Chattisgarh	Raipur	1	1	2010	Rice - Vegetables	0.6	36% more yield and 45% less water use
Bihar	Gaya	1	4	2013	Rice leaf – Vegetables Taro	1	15% - 25% more yield and 50% less water use

State	District	Area Under Drip (acre) [1ha= 2.5 acre]	No of Farmers	First Installation date	Crop Cycle (Rice + Rotation Crop)	Drip line space (m)	Yield change and water economics of rice crop
Maharashtra	Raigad	1	1	2010	Rice	0.6	41% more yield and 55% less water use
Rajasthan	Kota	15	1	2010	Rice	1	15% more yield and 40% less water use
	Kota	10	1	2009	Rice - Garlic	1	28.5% more yield and 40% less water use
Punjab	Patiala	4	1	2011	Rice- Wheat	0.6	18 – 28.6% more yield and 30% less water use
	Patiala	1	1	2013	Rice- Wheat	0.6	20% more yield and 55% less water use
	Patiala	3	1	2019	Rice- Wheat	0.6	25% more yield and 40% less water use
	Navashahar	0.5	1	2010	Rice- Wheat	0.6	25% more yield and 40% less water use
Tamil Nadu	Cuddalore	2.2	2	2013 & 2018	Rice – Vegetable & Pulses	1.2	20% - 30% more yield and 50% less water use
	Karur	1.3	1	2019	Rice - Pulses	1.2	25% more yield and 55% less water use
	Madhurai	0.5	1	2013	Rice - Pulses	1.2	30% more yield and 50% less water use
	Thanjavur	2.2	3	2017 & 2020	Rice - Pulses	1 & 1.2	20% more yield and 50% less water use
	Thiruvarur	3.5	3	2018 & 2020	Rice – Pulses & Groundnut	1.2	20% - 25% more yield and 40% - 50% less water use
	Thiruvannamalai	0.5	1	2013	Rice – Vegetable	1.2	30% more yield and 55% less water use
	Thirupur	0.8	1	2007	Rice - Pulses	0.6	22% more yield and 55% less water use
	Thirunelveli	9	1	2019	Rice – Cluster & Onion	1.2	10% more yield and 50% less water use
	Trichy	2	2	2014 & 2018	Rice	1	10% more yield and 50% less water use
	Tuticorin	1.1	1	2019	Rice – Pulses	1.2	23% more yield and 45% less water use

Data collected during a period 2009-2019 from farmers of different districts (spread in many States) of India.

Economic benefits of drip are analyzed using field data collected from different locations (Table 7).

Table 7. Summary of cost and benefits accrued to the farmers who adopted drip irrigation for rice cultivation.

State	Punjab	Rajasthan	Chhattisgarh	Andhra Pradesh
Farmer details	Didda Singh, Mahalo, SBS Nagar Dist.	Rajesh Vijay, Bhadana village, Kota dist.	Nanda Kumar Varma, Pirda, Durg dist.	Siva Reddy, Buddaipally, Kadapa dist.
Rice variety	Arize, 6129	Pusa-4 (1124)	1010	MTU 4870
Crop area	0.5 acre	15 acre	1 acre	0.5 acre
Yield	3.24 t/acre	1.2 t/acre	3t/acre	3.8 t/acre
Incremental yield (due to drip)	0.8 t/acre	0.6 t/acre	1.0 t/acre	1.5 t/acre
Cost of Cultivation	9,260 /acre	11,000/acre	9,000/acre	13,300/acre

State	Punjab	Rajasthan	Chhattisgarh	Andhra Pradesh
Cost of drip equipment	30,000 /acre	60,000/acre	28,000/acre	45,000/acre
Subsidy for equipment ##	18,000/acre	42,000 /acre	nil	40,500/acre
Life of the equipment $$	7 years (14 seasons)	7 years (14 seasons)	3 years (6 seasons)	7 years (14 seasons)
Seasonal cost of equipment	2142.9 Rs /acre	4285.7 Rs /acre	4667.00 Rs/acre	3214.3 Rs/acre
COP + equipment cost (seasonal)	11,402.9 Rs/acre	15285.7 Rs/acre	13667.00 Rs/acre	16514.3 Rs/acre
Gross income	35640 Rs/acre	44,000 Rs/acre	34,500 Rs/acre	38,000 Rs/acre
Net income	24,380 Rs/acre	28714.3 Rs/acre	20833 Rs/acre	23867 Rs/acre
B C ratio	2.1	1.9	1.5	1.4
Pay Back period&&	1.23 seasons (= 1 year)	2.09 seasons (= 1 year)	1.3 seasons (= 1 year)	1.9 seasons (= 1 year)
water saving % **	40	40	35	45

** As % of water applied in conventional flooded plots.
$$ Drip equipment is generally used for 7 years; total of 14 crops on rotation.
Subsidy component (assistance by Government) is not considered for B C and Payback period estimates.
&& Income from rotation crop (Rotation crop after rice) is taken as equivalent to rice net income.
Source: Soman, 2012

In all these demonstrations farms' drip field recorded higher yields than what the respective farmers used to get in conventional cultivation. On average, the investment cost of the equipment could be recovered within a year, in two seasonal crops. Introduction of Government subsidy for drip equipment for rice, as done in the past for many other crops, is a major policy intervention expected. Most of the framers who participated in the demonstrations already had drip equipment obtained for other crops, that could be easily modified for rice crop planting pattern.

Irrigation water could not be metered in the farmers' fields. However, from the pumping data, the water use for drip could be estimated.

5. Commercialization of the technology

5.1 Building reach

While the experimental and farmer field data are promising for the introduction of the technology, it may not be an easy ride all the way through. The attitudinal change among the farmers to accept the new method of irrigation for rice, is a challenge. The following steps are taken to accelerate the process: working in collaboration with public, scientific and extension institutions, national agriculture research bodies, regional research stations, Krishi Vigyan Kendras (KVK, a local government source for agriculture extension), International Agriculture Research Institutions, and progressive farmers; and participation in National and International seminars and conferences (Soman, 2012; Soman et al., 2018c).

Regional rice research stations are keeping drip irrigated rice plots for visiting farmers. Technology is also tested in collaboration with the International Rice Research Institute (IRRI), Manila, at Los Banos, Philippines, and Varanasi and Modipuram, India for the last four years and with International Water Management Institute (IWMI) in Medak, Telengana. Jain Irrigation systems Ltd., partners with research organizations both in the area of rice research and water management.

Among the multiple reasons for the poor adoption of the drip technology is the huge *mental block*; farmers cannot conceive the idea of rice crop growing without standing water. The tradition is very strong and has been followed by generations. One of the concerns is the perception that weeds in the absence of standing water would be difficult to control. Introduction of husk mulching or limited use of herbicides are solutions; but farmers fear about the cost and the additional work involved.

Table 8. Performance of a rotation crop after the main rice crop under drip irrigation and the enhancement of annual return from the farm.

Farmer Details	Kharif (rainy season) Crop	Yield t/acre	Gross Income/ acre	Cost of Cultivation Rs/acre ($ = 82.00 Rs)	Net Rs/ acre	Rabi (dry season) rotation	Yield t/acre	Gross Income Rs/acre	Cost of Cultivation Rs/acre	Net income Rs/acre	Annual Net income Rs /acre
Sri.T. Mahipal Yadav, Chintelpet, Karimnagar	Rice -MTU 1010	3.6	48600	22800	25800	Rice	2.6	35100	21250	13850	39650
M.Veeraraju chowdary, Kotapadu, E.Godavari	Rice-BPT 5204	3.4	50625	21600	29025	Maize	5.2	65000	14250	50750	79775
MVV, Satyanarayana, Nallamilli, E.Godavari	Rice-Swarna 7029	3.6	52560	22500	30060	Brinjal	40	120000	20500	99500	129560
Srimati. Kranthi, Itlamamidipalli, Vijayanagarm	Rice- Arize 6449	2.9	43875	19750	24125	Gherkins	16.5	148000	47500	100500	124625

More focused extension and farmer awareness programs both by private supplier companies and government departments must come into the force. There are successful farmers who use the drip technology for rice and then the rotation crop (wheat or mustard in Haryana, Punjab, a second rice or pulses or vegetables in Andhra Pradesh and Tamilnad). Their experiences must be highlighted and spread across all rice growing regions.

A second factor is the cost of drip system which varies from 65,000 to 100, 000 Rs per ha (790-1220 $) based on the soil textural type. This issue known to the government and although subsidy assistance was not there for cereal crops in the past, the situation is slowly changing. A few State governments, Andhra Pradesh for example, began the process of providing financial assistance to small farmers for rice as well.

Table 8 demonstrates the overall economics of the drip system with first rice crop followed by a rotation crop. The overall income from a unit of land has gone up annually. This is another factor encouraging the farmers to adopt drip irrigation for rice. There should also be interventions at the policy level even incentivizing the farmers to adopt the drip technology.

6. Environmental issues

Apart from the water conservation issue by the large-scale adoption of the drip technology; conversion of one acre into drip from flooding would, based on field data, generate sufficient water for another 2.9 acre rice or 3.2 acre vegetable crop, drip adoption would result in other benefits in areas crucial to the sustainability of the environment.
Emission of methane gas in rice ecologies is a major environmental issue; one of the factors resulting in methane emission from rice fields is the standing water and the anaerobic decomposition of organic matter. In the non-flooded situation, like drip irrigated rice, the conditions for methane formation would be minimal. However, quantification of the methane gas emission from drip fields is yet to be confirmed. Collaborative research of Jain Irrigation systems Ltd with IRRI on these aspects is currently in progress at IRRI's main campus in the Philippines and the Indian IRRI station at Varanasi.

Similarly, fertigation, application of fertilizer as a dilute solution in multiple doses for rice crop, would also bring down nitrate pollution into community water bodies. It is also noted that in rice dominated villages the standing water provides a suitable environment for mosquito breeding and diseases transmitted through them.

7. Water productivity of rice

Water use by rice crop includes transpiration by rice plants, and evaporation from the rice growing field; these two are essential components of the water *fate* of the crop; seepage and percolation into the soil profile of the field, the two non-essential components of the water consumption in a rice field.

Studies at IRRI estimated the transpiration from rice plants range from 500 to 1000 liter per kg unmilled rice. The average evapotranspiration from a rice crop is 1432 liter/kg unmilled rice growing in controlled conditions. This is the same as the world average water use for wheat. Rice field water use (ET plus Percolation and Seepage) is estimated to be 2500 l/kg unmilled rice (Bouman, 2009). For every kg rice 1000 litre of water is wasted into the soil profile! As we are staring into a future with a reality of water stress (physical shortage) rice irrigation needs to change; change should avert that 1000 litre of water go into the deep soil and a change to reduce the water from the 2500 litre that currently produces a kilogram of unmilled rice.

It is imperative to modernize irrigation methods and achieve precision in irrigation to restrict the water application only to the extend equivalent to the Evapo-Transpiration (ET) of the crop. Apply only what is required at each time / stage of the crop. Jain Irrigation systems Ltd field studies with metered water supply through drip method repeatedly showed that 1 kg of unmilled rice used only 1724 liter of irrigation water (Table 8).

Drip irrigation and fertigation together can deliver the two major inputs for crop production; water and minerals, and result in enhanced productivity from unit land area with highest possible efficiencies of water and fertilizer use. Extensive data collected from farmers' fields in Haryana, also showed the higher water use efficiency of rice under drip irrigation (Soman et al., 2018c).

In an on-farm study project,–"Water Productivity in Cotton and Rice", Swiss Development Corporation (SDC) funded part of the cost of drip systems supplied to the project farmers and Jain Irrigation Systems Ltd., the technology provider in addition to implementing the project and providing agronomy support to the farmers. The project farmers are all Basmati Variety of rice growers from Kaithal, Kurukshetra and Ambala districts of Haryana. The Jain Irrigation Systems team identified 19 farmers in these districts who agreed to take up drip irrigated rice cultivation.

Table 9. Water productivity in flooded and drip irrigated rice (kg/m^3) *

Variety	Flood rice	Drip
SBH-999	0.13	0.67
25P25	0.1	0.57
25P31	0.14	0.62
MAS- 946-1	0.14	0.52
Try (R)-2	0.13	0.53
BPT	0.1	0.46
Pusa Sugandha	0.12	0.7
Mean	**0.12**	**0.58**
Water required to produce 1 kg unmilled rice	8333 l/kg	1724 l/kg

*Soman et al. (2018a)

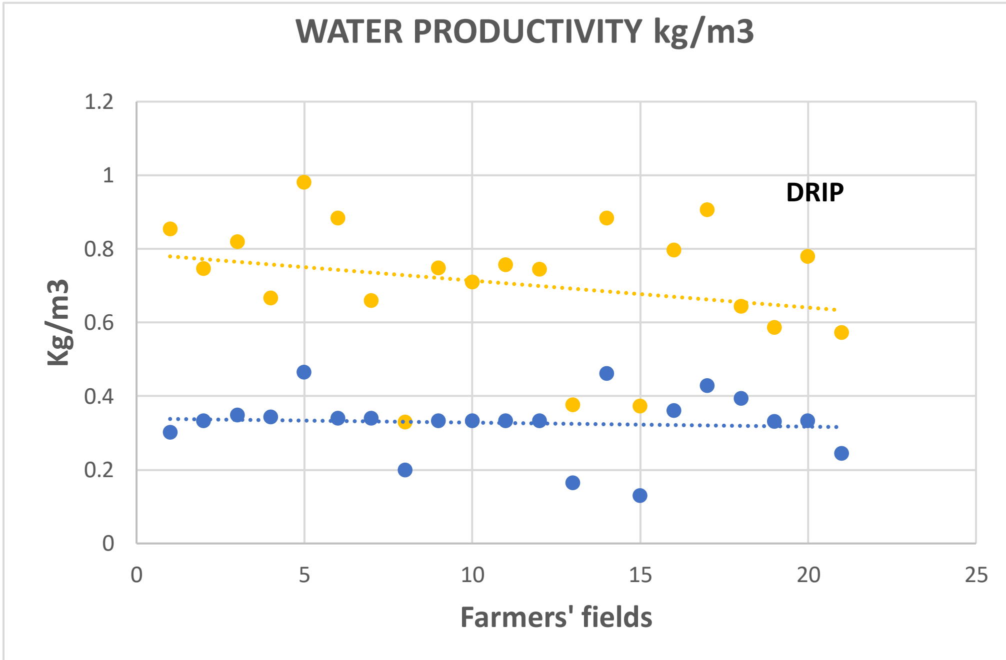

Figure 2. Irrigation water productivity of single season rice under flood (Blue dots) and drip (Yellow dots) methods of irrigation; data recorded in the On-farm study in Haryana state (Soman et al., 2021).

The water productivity (based on irrigation water only) was always superior in drip irrigated rice –trending around 0.8 kg paddy grain/m^3 as against 0.3 kg/m^3 in flood irrigated fields (Fig 2). Irrigation water productivity (IWP) even of a single variety of rice can't be a constant figure in different locations and under various crop management methods and crop seasons. IWP is also not just dependent on water consumption alone, as other inputs affect the productivity. Soman et al. (2021) found that the Irrigation water productivity obtained in flood and drip irrigated situations differed in absolute values from those obtained in the present study. But a comparison of IWP in flood and drip methods of irrigation is relevant for similar crop management situations in the same season.

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RICE CULTIVATION IN THE MEDITERRANEAN REGION: ITALY CASE STUDY

Dr. Arcieri, Marco[1]

ABSTRACT

In recent years, human consumption of rice as a staple food for rural communities has been steadily increasing in the Mediterranean area. Hence, it can well be considered as a strategic crop for food security, especially for the rural communities. In the whole sea basin, it is cultivated over an area of about 1,300,000 hectares, the most important producing countries being Italy and Spain within the European Continent (72% of the EU production; 345,000 ha), Egypt and Turkey among the Mediterranean countries (almost totality of the production; 789,000 ha). Traditionally, in this area rice is grown under continuous flood irrigation, hence it requires much more irrigation than non-ponded crops: as a matter of fact, on average rice cultivation requires from 15,000 to 20,000 m^3 per ha of water per season.

Keywords: rice, Italy, irrigation, climate change.

1. Introduction

In the last few years, the main objectives of research and experimentation in rice cultivation have been focused on the strategic goal of finding new solutions for the optimization of water use, besides reducing its impact on the environment. These goals can be achieved by the introduction of alternative irrigation systems, new cultivation strategies, and by the development of specific indicators, developed and conceived to assess the environmental, economic, and social impact of various irrigation management approaches. Furthermore, many studies are currently aimed at the possibility, also, to extend rice cultivation outside the traditional paddy areas, so as to meet the escalating demand for this staple food. Results obtained by recent research have allowed for the development of updated and new custom-made technologies, according to different areas of production, paying great attention to the sustainability of rice production in different countries of the Mediterranean region, with a particular consideration for the adoption of water-saving techniques.

The main barriers to the achievement of these have proved to be the economic sustainability of the proposed innovations and the initial reluctance of rural communities and farmers to accept them. For this reason, projects have often carried out assessment of the overall sustainability regarding innovative irrigation solutions, besides the possibility to improve communication among all the stakeholders involved. Also, the preparation and dissemination of technical documents with description of best practices conceived to support the effective implementation of new irrigation solutions, and the transfer of projects' results to the agricultural sector and to decision makers can be acknowledged amongst the most important outputs. This report, thus, aims to enhance the understanding of water quantity-quality and environmental issues in the rice cropping systems of the largest rice cultivating area in Europe, facing these problems both at the farm scale and at the district scale, proposing new innovative water management approaches in the cultivation.

2. Rice cultivation in Italy

Italy is the leading rice producing country in the European Union (EU), characterized by a high-quality level of its yields: about two thirds of Europe's rice are produced in Italy, with 60% of the national production exported to EU (two-thirds of the exported amount) or to other countries, mainly in the Mediterranean region and Eastern Europe. Rice production started in Italy around

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the middle of the 15th century, greatly influencing its distinguished cuisine, after it was introduced by the Arab domination throughout the Iberian Peninsula in the 12th century.

Today, this cultivation in Italy is highly specialized and makes for 70-80% of the rice farming surface. Italian paddy systems are in the most northern latitude, where water plays a fundamental role in thermoregulating the growing process, because the adopted flooding irrigation keeps the daily variations in temperature from 10-15 °C to 3-4°C. The largest rice producing areas are Lombardy and Piedmont regions, even though important areas of production have also developed in time throughout Southern Italy regions such as Calabria and Sardinia Island (Figure 1).

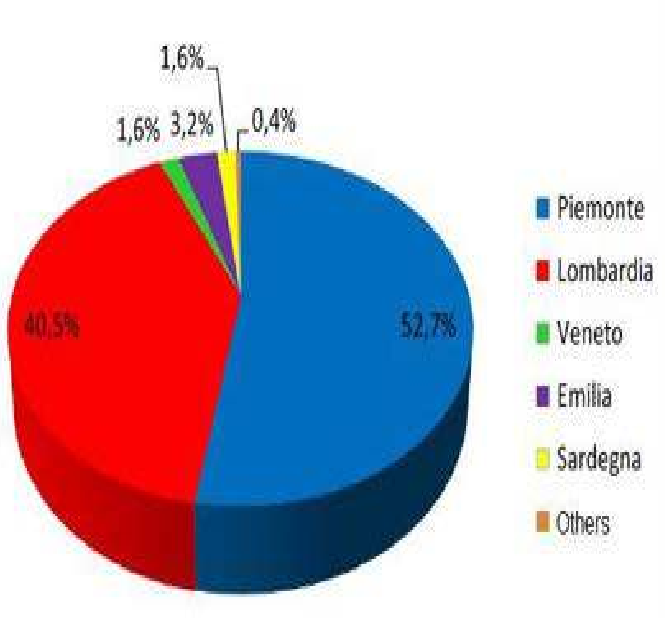

Figure 1. Regional distribution of paddy fields in Italy (Arcieri et al., 2020).

By far, the most important rice-growing area is the portion of the Padana plain located on the left bank of the Po River and running along the Ticino River, spanning through the Lombardy and Piedmont regions of northern Italy. Flooding technique for paddy irrigation is practiced over 10% of the total national irrigated area, where the basic condition is to keep a water depth of about 0.1-0.3 m above the soil surface.

During the past years, the cultivated area had been increasing, thus bringing a positive impulse to the Italian economy because of the significant export of its total production, which counterbalances the imports of large quantities of food and feed products coming from abroad. As a matter of fact, Italy has become an important rice-exporting country, considering that its domestic consumption hardly exceeds 40% of the total rice production.

The crop is grown from April to October and extends over about 200,000 ha, roughly 1.5% of the total arable area of the country. The production is approximately 1.4 million metric tons of paddy rice with an average yield about 6 tons per ha, 85% of the surface being cropped with "*Japonica*" type varieties, the rest with "*Thaibonnet*". Although Italian rice production represents a very small fraction of the world production, the volume of exports reaches 5% of total rice traded in the world.

Most of paddy rice systems are located in the "Padana" (Po River) plain, between the alpine lakes and the left bank of the Po River. Water supplied to the irrigated fields is mostly taken from the so called "risorgive" springs and, to a smaller extent, from alpine rivers. The term risorgiva applies to the out surge of natural groundwater occurring where the hill slope reduces, when meeting the plain (Figure 2).

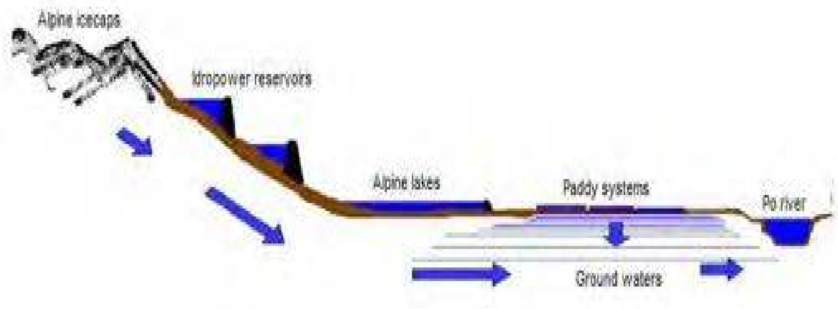

Figure 2. Paddy systems within the water cycle; downstream the "*risorgive* belt", North of the Po River (Arcieri et al., 2020).

The average temperature of water from springs ranges between 10° and 14°C all year round; this is very important from the ecological perspective since microclimatic conditions can have positive effects on the flora and fauna populations, in addition to maintaining biodiversity.

Figure 3. Paddy fields in the western Padana plain (Arcieri et al., 2020).

In the western part of the production area (i.e., Piedmont and Lombardy), the average size of the cropping unit is about 2 to 3 ha, due to some ground slope and soil permeability issues (Figure 3). In the eastern part (i.e., Veneto and Emilia Romagna), where the ground is flat and soil permeability is lower, plot size is about 10 to 12 hectares on average.

Figure 4. Typical "caldane" in the western Padana plain (Arcieri et al., 2020).

Water springing from *risorgive* is naturally filtered, therefore it is clear and pollutant free. On the other hand, water coming from western alpine rivers is colder, especially during the ice cap melting in spring. The use of this source of water in paddy systems hence requires some temperature increase before field application.

Water heating occurs prior to the field inlet, in a small area called "*caldana*", where water movement takes place over a long route according to a comb-shaped flow (Figure 4). Field size depends on different factors, among which soil type, topography, and land arrangement which identify paddy rice systems both in the western and in the eastern part of the Padana plain.

PREPARATION OF THE PADDY FIELD AND SOWING

In Italy rice is a typical spring-summer crop, being grown from April to October with a usual crop rotation of maize, beet and vegetables. At the end of the winter season, a surface light ploughing (20-25 cm) is carried out with a mold-board plough; this eventually can be replaced by hoeing or digging on light, organic soils, in order to proceed to fertilization. Just before sowing a light tillage, organic harrowing and a surface levelling (with laser system) can be carried out in order to obtain well-levelled fields.

Figure 5a. Typical flooded sowing in the western Padana plain (Arcieri et al., 2020).

Figure 5b. Typical dry sowing in the western Padana plain (Arcieri et al., 2020).

These are usually surrounded by embankments and served by a well spread network of supply and drainage canals, even though the annual maintenance of canals and embankments is quite expensive. Transplant was once widespread in Italy (today it is only in Tropical Countries), especially to shorten the cycle in cold environments, but required a lot of manpower. So, today direct sowing is by far the most frequently used technique, either carried out on flooded (Figure 5a) or dry rice paddy surface (Figure 5b). Usually, rice is grown in shallow water (10-30 cm), depending on the height of rice and weeds.

There is a constant need to keep running water, because of the high demand for O_2 of seedlings and roots and, of course, to have an efficient thermoregulation, avoiding the use of cold water. Early sowing is better for late ripening cultivars, but it can be somewhat risky for cultivars with high thermal requirement (for the ssp. indica).

Water management

Rice is a highly water demanding plant. Its cultivation requires a great availability of water resource, as water shortage can affect normal growth of the crop, reducing yields. Traditional cultivation technique, such as the submersion system of the Padana plain paddy fields (Figure 6) requires high volumes of water, ranging on average between 15,000 and 20,000 m^3 per ha, depending on the season.

Figure 6. Typical submerged rice cultivation in Northern Italy (Arcieri et al., 2020).

But even though it is usually harvested as a submerged crop, after emergence at least 3 dry cycles are usually performed (Baldoni, G., 2008) during the phases, as depicted in Figure 7, showing typical cultivation cycle in the provinces of Vercelli and Ferrara:

- Tillering (with 2-3 leaves) - at half of June
- Fertilization and weeding - at the end of June
- Before harvesting (ripening) - that is at the end of August or September, according to the growing area.

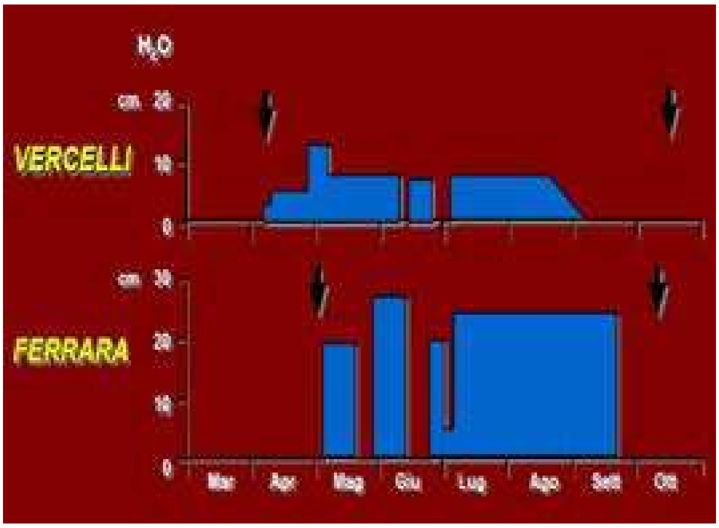

Figure 7. Typical irrigation pattern for rice in the western Padana plain (Arcieri et al., 2020).

Water comes from collective irrigation systems, wells, springs or rivers. The level is continuously adjusted, according to the thermal demands of the crop, but also in order to avoid incidence of pests and weeds. Water temperature has to be kept between 12 and 14°C (April-May in Northern Italy). This is the reason why water is warmed up by winding through typical canals exposed to direct sun, called *caldane*, specifically designed in order to raise water temperature before it gets to the rice fields. (Figure 4).

Harvesting

Harvesting period in Italy can be so classified:

- Early cultivars: Half of September
- Late cultivars: Mid of October

Yields usually range between 6 to 7 t/ha of paddy rice with 13% moisture content, which is higher than the world average (4.0 t/ha). In dry paddy field (2 weeks before cropping), harvesting is carried out with a 23-25% of humidity. The drying up process (to 13-14% of moisture) occurs in dryers at 35-40°C.

Figure 8. Rice harvesting in the Padana plain.

In some areas of the country manual harvesting and grain separation can be still found, but usually in specialized areas it is done by means of half-tracked or normal combine, with a 3-5 m working bar and a labour capacity of 1h per ha (Figure 8).

Main constraints

Main problems for the cultivation of rice in Italy are:

Climate: it remains the most limiting factor, considering that the rice area is mostly located in the northern part of Italy (> 45°N). Cold temperatures (5°C or less) and frost events (Figure 9) can often occur at sowing time (in April), creating damage to seedlings and causing poor establishment in rice fields.

Figure 9. Typical frost event on rice cultivation in the Padana plain.

Moreover, a sudden decrease of temperatures or strong diurnal variations can occur at flowering time, because of thunderstorms in August (Figure 10), causing spikelet sterility and/or more favourable conditions for blast attacks. In recent years, storms and strong winds during the ripening stage caused severe lodging of the tallest varieties.

Figure 10. Typical summer thunder storm on rice cultivation in the Padana plain.

Diseases: blast and brown spot are at present the main diseases, but they rarely cause great damage to the crop, depending on climatic conditions. Weed populations remain one of the main limiting factors for rice production in intensive cultivation conditions of northern Italy (Figure 11).

Figure 11. Typical infesting weed of rice cultivation *Cyperus difformis*.

Amongst others, red rice has become a main constraint in the last years as it is highly persistent in soils, especially in the case of monoculture.

Many studies and research results have proven that possibility exists to increase the potential yield by means of varietal improvement, with emphasis on disease resistance, lodging resistance, low temperature and dry conditions adaptability.

Key challenges

The key challenges that cultivation of rice in Italy faces are:

- Improving mercantile quality of national productions, in order to adequately meet requirements of a fast-growing changing market, especially oriented to Far East demand (Figure 12).

Figure 12. Typical characters of grains from rice cultivation in Italy

- Coping with growing costs of agricultural inputs & declining of real farm incomes, due to instability of prices.
- Increasing global competitiveness under liberalized trade conditions and stock exchange fluctuations.
- Improving small farm production efficiency, by promoting a new ecosystem-based agriculture, within the context of sustainable intensification and climate change.
- Raising rice productivity, thus making the farmer more profitable, globally competitive and climate-resilient, by producing more with less resources (Figure 13).

Figure 13. Typical rice field in northern Italy at harvest.

Key issues

The key issues for the cultivation of rice in Italy at present are:

- Increased unpredictability, severity and frequency of extreme weather events, such as powerful thunderstorms and intense rainfall. Much more often than in the past, due to the constant raising of temperatures witnessed in the Mediterranean Sea, the formation of the so called “Mediterranean hurricanes” is recurrent (Figure 14).

Figure 14. Hurricane formation in northern Italy.

- Growing proportions of rice cultivated in now drought-prone areas, where intense urbanization is diverting irrigation water for domestic use, creating unpleasant conflicts between territories and triggering competition among users (Figure 15).

Figure 15. Competition for water is also constraining rice agriculture in northern Italy.

- Far more frequently recurring high temperatures, which create difficult conditions for the cultivation, besides increasing pests and diseases occurrence (Figure 16).

Figure 16. Increasing temperatures are seriously constraining rice agriculture in northern Italy.

Water scarcity, which has indeed become a serious limiting factor for production in Northern Italy, as almost 60% of freshwater resources flow directly to rice paddies (Figure 17).

Figure 17. Water scarcity has been severely affecting rice cultivation in recent years.

3. The Way Ahead: Dry Cultivation, Alternate Wetting and Drying (AWD) Technique, Organic Rice and Drip Irrigation.

As seen, climate change and price unpredictability represent severe challenges for Italian producers, as agricultural companies are called to adapt their production processes to the needs of the globalized market. At present, no increase in the rice cultivation area in Italy is expected in the nearest future whereas, on the contrary, a further decrease might probably occur if the rice price is going to decrease, or production will be affected by global market dynamics. Thus, a general increase in rice yields can generally be expected by means of introduction of new varieties with improved traits, such as disease resistance, salinity and low temperature tolerance, reduced culm length and increased lodging resistance also, by adoption of new cultivation techniques and innovative water resources management strategies/systems. This is why, in recent years, Italian rice cultivation has been going through a phase of great transformation, given the advances in the alternative procedures. One of these is the dry cultivation.

3.1 Dry Cultivation

The development of rice cultivars with improved tolerance to reduced water regimes (upland like) offers today very interesting perspectives and represents a major objective of research in order to save water. As a matter of fact, the repeated occurrence of particularly dry weather conditions in recent years has created conditions of water scarcity in Northern Italy, with serious consequences on yields of the main irrigated crops, such as rice. When dealing with dry cultivation, sowing is carried out on dry soil, burying the seed at a 2-3 cm depth and water requirements are postponed by about 30 to 45 days. After this phase the cultivation remains flooded, and water management is very much similar to a traditional paddy field. This practice guarantees a favourable environmental impact because of the reduced water requirements, the lower energy demand and the minor incidence of weeds. Under this water regime plants receive about 1/5 of the total water volume needed for conventional culture under submersion.

The advantages of practicing a dry seeding can be defined as:

- lower amounts of water required (20% less is needed compared to conventional seeding);
- lower emission of water vapour and gas caused by fermentation;
- lower mosquitoes and similar insects' occurrence, as well as lesser herbicides in the ground;
- less nitrates and lower maintenance of the embankments required.

A very interesting example of this new approach in research has been the CEDROME Project (Figure 18) funded by the European Commission EU which aimed to "Develop drought-resistant cereals to support efficient water management in the Mediterranean area" is an example of these. Within the framework of this Project, a two-year field trial has been carried out, performing an assessment of 7 Italian rice Cultivars evaluated for the main agronomical, quality and phytosanitary traits, comparing the conventional submersion systems with the so-called upland system.

Figure 18. Experimental site of the CEDROME Project in Vercelli, 2006.

It has been observed that water shortage caused a yield reduction of 40% on average, due to the decrease in the 1,000 seed weight, a lower tiller density and panicle sterility. However, three cultivars out of the seven assessed showed a considerable good performance under water stress conditions, showing very interesting yield and milling results. When compared to conventional culture conditions, yield of these three Cultivars reached values of about 80% of the total, showing the highest values of WUE. Moreover, the optical microscope analysis of the root system of plants grown under reduced water regime has highlighted a significant difference between the two growing conditions. The roots grown in submergence expressed a total absence of fungal colonization, as compared to those growing in condition of dryness. On the other hand, dry land conditions stimulated in rice roots a natural colonization with Arbuscular Mycorrhizal (AM) fungi, which are well known to play a beneficial role in the general physiology and nutrition processes of the plant (Cavigiolo et al., 2007).

3.2 Alternate Wetting and Drying (AWD) Technique.

A similar, interesting recent approach in rice cultivation is the Alternate Wetting and Drying (AWD) technique, which has been developed and evaluated on rice systems in several countries now, besides Italy (Gilardi et al, 2023). The AWD has been introduced in order to reduce water consumption, to increase water use efficiency and to reduce negative effects of permanent flooding, like the upsurge in methane emissions and arsenic availability in soil, as well as to reduce greenhouse gases emissions. Therefore, there is growing interest in evaluating the introduction of this water-saving technique for rice cropping, also in Italy. In AWD, rice fields are allowed to dry naturally for one or more days after the disappearance of ponded water, up to a given soil moisture content or water table depth and then re-flooded. Maintenance of yield and plant production levels close to continuously flooded rice can be achieved as long as re-flooding occurs before plants become drought-stressed, and AWD can even improve yield by increasing the proportion of productive tillers.

It has also been shown that AWD can reduce soil availability of arsenic (As) and its concentration in rice grains, while cadmium (Cd) availability and uptake is favoured under oxidizing conditions and may lead to high concentrations into grains, which is a serious human health problem (Cattani et al., 2008).

These are the main reasons why the feasibility of intermittent irrigation, without ponded water, has been recently tested in the Northern Italy rice area in terms of yield, water productivity, greenhouse gases emissions and economic results by several authors (Miniotti et al., 2016; Monaco et al., 2016; Peyron et al., 2016), even though very few studies have been focused on AWD systems as a viable option for this region (Verhoeven, 2018). Therefore, interest in testing a suitable water-saving technique which could limit rice water stress, while keeping rice yield acceptable, has risen significantly.

For this reason, it may well be worthwhile citing a two-year field experiment that has been carried out in the agri-environmental conditions of the Northern Italian rice area, with the aim of testing the feasibility of a mild AWD system, i.e., only implemented during the vegetative phase, and to evaluate the adaptation of a set of representative European rice varieties to this system.

Figure 19. Experimental Farm Station of Cascina Boraso (Vercelli) in Northern Italy.

The field experiment compared an AWD system with a dry-seeded system characterized by postponed flooding; this was part of a larger research project on the application of AWD in the European rice sector and on the adaptation of European cultivars, with parallel field experiments in Delta Ebro area (Spain) and Camargue (France). In Italy, the experiment was carried out in a paddy field of "Cascina Boraso" (Figure 19), an experimental farm research station (45°19'24" N; 08°22'25" W) in the Vercelli district, which along with Novara and Pavia districts, represents the most important rice production area in Italy and Europe. The average temperature during the growing period, from the 1st of May to the 30th of September was very similar in the two years (i.e. 22.8 and 22.7 °C in 2015 and 2017, respectively), and higher than the period 2007–2014, which was used as a reference (21.3 °C). Total cumulative precipitation in the rice growing period was equal to 130.5 and 111.6 mm in 2015 and 2017, respectively, and it was lower than the reference period. Parallelly, a set of 12 representative European varieties were evaluated at field scale for their potential adaptation to a mild AWD system, consisting in avoiding permanent flooding conditions while limiting water stress from sowing to flowering, and then maintaining ponded water as in the traditional continuously flooding system. About 1,435 mm of irrigation water consumption were estimated in this experiment in AWD, which are in the range calculated by Mayer et al. (2019) for AWD in the Northern Italian rice area.

The results of this field experiment showed that, under the pedoclimatic conditions and given the particular rice farming systems of Northern Italy area, it is possible to apply a mild AWD technique, maintaining it during the vegetative phase only, with very limited effects on crop status and final productivity. The consistency of this mild AWD is also applicable to a set of 12 representative European rice cultivars, which showed comparable adaptabilities among them, in terms of both yield and yield components. Therefore, it is not too inaccurate to state that the adoption of the AWD technique might be a very promising strategy for the future of water management in rice cultivation, in order to save water and to increase water use efficiency.

Many other similar experimental field trials have also been carried out under the framework of the "MEDWATERICE Project: towards a sustainable water use in Mediterranean rice-based agro-ecosystems". Funded by the EU, this project has been focusing on the possibility to explore sustainability of innovative irrigation systems on rice, in order to reduce water consumption and environmental impacts of its cultivation, besides exploring the possibility to extend rice cultivation outside of traditional paddy areas, in order to meet the growing demand of the world. Countries involved were Italy, Spain, Turkey, Egypt, Spain and Portugal. Most of the projects carried out in these Mediterranean regions, have been focused on water saving technologies at farm scale. Activities included collection of existing data, diagnosis of major problems affecting rice production in each country, identification and test of alternative water saving techniques tailored to local conditions (Figure 20).

Figure 20. Field data collecting in North East Spain rice field.

A minimum common database ensured harmonization of data collection, comparability of results, and overall sustainability assessment. Information gained included agro-meteorological and climatic data, soil physio-chemical properties, groundwater levels, irrigation water quality, field water balance components, and crop yield. Specific environmental issues (salinity, pesticides fate, greenhouse gas emissions, and reuse of treated wastewater) have also been investigated. Outcomes of the Project have then been used to upscale the effect of on-farm water saving technologies to the irrigation district level, and to quantify the impact of these technologies on food security and safety. The procedure for sustainability assessment of rice production in Mediterranean areas has been based on the selection and application of the most appropriate set of techno-economic and environmental impact indicators at the farm and irrigation district scales (Mayer et al., 2019). Regarding the social aspects, farmers, farmers' organizations and consultancy firms, irrigation water managers, policy makers and experts have been consulted to investigate the social acceptability of the proposed irrigation solutions. For instance, at the farm scale experimental/demo fields have been set up to compare different irrigation management options.

Usually, two Pilot Farms were involved in the studies: in the first farm, wet seeding and traditional flooding, dry seeding and delayed flooding, wet seeding and alternated wetting and drying were compared (Figure 21a).

In the second farm, the current system of manually opened sluice gates for the wet seeding and traditional flooding irrigation management was compared with electro-mechanically controlled gates, allowing a more accurate water management (Figure 21b).

(a) **(b)**

Figure 21. Farm scale field trials on rice in North East Spain.

Water use efficiency (WUE), yield and quality of the production, besides environmental impacts on surface water and groundwater for each irrigation treatment have also been quantified.

The irrigation district scale (about 103-104 hectares) investigation has also proven to be crucial, when goal is to support decisions of authorities that deal with water resource planning and management at the regional scale. Rice fields are not isolated units, but are part of large and homogenous areas where strong intra-field interactions may occur, particularly when flooding is the irrigation method adopted (Figure 22).

From the perspective point of view of the entire irrigation system, amounts of water losses at the field scale (i.e., percolation below the root zone, surface or sub-surface drainage to ditches or other fields placed downslope, in a field topographic sequence) are reused. Consequently, when water use efficiency (WUE) is computed at the irrigation district scale, water reuses must be taken into account, and may significantly increase the WUE value. To upscale the results measured at the farm level, agro-hydrological models have also been used.

Figure 22. Large irrigation district scale field trials on rice in North East Spain.

3.3 Organic rice.

Organic farming continues its double-digit growth trend: in 2016 food sales has increased by 20% (Willer et al., 2018). As recent market research highlighted, there is a growing attention of consumers to know about the properties of raw materials, their origin, and if they're obtained as a result of sustainable production respectful of the environment. Behind this desire for traceability, there is an increase in the demand for organic food products, safe from a human food point of view, but also respectful of the environment. This is why in recent years, many Italian farmers have introduced alternative techniques in rice cultivation such as mulching, usually used to grow other vegetables (Figure 23).

Figure 23. Rice field covered with organic mulch films in north west Italy.

This has been possible after the introduction of bio degradable sheets, made of organic material, such as potatoes and corn residues. Films are laid out in paddy fields to prevent weeds' growth and avoid chemical products. Mulch is provided by a different machine spreading the sheets and creating special holes, where rice seeds are released (Figure 24).

Figure 24. Laying of mulch film on rice field in north west Italy

Rice seedlings are so enabled to grow, while weeds remain suffocated under the covering film, which allows very little light to filter. Organic rice cultivation, with its 12,500 hectares, today only represents 6% of the rice cultivated area, but about a quarter of the land is now under conversion. In the next few years, mulching is expected will cover about 10% of the organic rice area in Italy: it still represents a niche at the national level, but portrays a future aimed at environmental sustainability and quality product. Several field trials are currently being carried out with this innovative technique.

3.4 Drip Irrigation on rice.

The contraction of the rice cultivated area, along with the reduction of yield due to the very recent years' drought have led to a significant decrease in the 2022 harvest. This means a production of about 260,000 tonnes, 16% less than what had been achieved in the 2021 campaign. Moreover, the overall availability of water for agriculture has especially decreased in traditional rice cultivated areas, due to the influence of climate change on the accumulation process of snow in the Alps, shrinking the glaciers from where major northern Italy rivers originally derive their flow, and on spring and summer rainfall. In addition to this context, environmental issues such as water quality and soil salinization seem also to be emerging, having a strong impact on production. This is why It has become essential for farmers to evaluate the use of innovative irrigation systems, alternative to traditional flooding.

Now, drip irrigation on rice in Italy has been studied and experimented on field during the last 15 years; it is undoubtedly an innovative approach for this crop which, if properly calibrated and managed, might allow to consume up to 40% less water than the traditional submersion system, (the average water footprint of 1 kg of rice is equal to 2,500 L of water) and use up to 25% less nutrients, without experiencing significant reduction of yields in terms of quantity, improving organoleptic characteristics of the rice.

Several field trials are being currently exploited nowadays in different areas of Northern Italy (Figure 25), especially in the north eastern regions of Italy (Veneto) and results seem to be encouraging. But what is most important, it can also allow for significant reduction of the environmental impact of the cultivation, considered that under aerobic conditions methane emissions are reduced by 75-90%. This last consideration is extremely relevant, as traditionally cultivated rice today accounts for about 20% of man-made methane emissions, an important greenhouse gas which, on a 100-year scale, has proven to be about 20 times more significant than CO_2. This potential emission is due to the prevailing anaerobic conditions occurring in the traditional rice agro-ecosystems, their high organic matter content and the overall massive cultivation of the crop worldwide.

Figure 25. Drip irrigation line in rice field in north eastern Italy (Veneto)

The possibility of applying drip irrigation for rice, thus, really opens up new scenarios, and since there is no longer need to prepare the paddy fields for submersion, rice can indeed become part of a crop rotation, with all the resulting benefits in terms of soil fertility, biodiversity and weeds and pests eradication. When properly dealt with some issues such as weed control and energy costs, it is our opinion that drip irrigated rice could become to all intents and purposes a cash crop, to be grown in areas other than the traditional ones, and on which farmers can decide to focus year by year.

3.5 Climate Change and rice production.

Drought and climate change have significantly slowed down the pace of growth in rice cultivation, and even though Italy remains the first producing country in Europe, producers look for new ways to safeguard production, economy and the environment. Exports volume to non-EU countries during the 2022/2023 campaign totalled almost 70,000 tonnes, with a drop of 27% compared to the quantities exported in the same period of the previous year campaign (Figure 26).

During year 2022, Italian rice cropping areas went down by about 4% compared to 2021, when almost 230,000 ha were cultivated. This drop has been mainly due to the scarcity of water recorded in many areas of the traditional Italian rice-growing area, which of course affected the choice of crops to grow. Furthermore, water scarcity has heavily conditioned yields: areas such as Novara and the province of Pavia have recorded the greatest reduction in production, respectively of 15% and 29%.

At the national level, the decline amounted to 16%. According to what has been declared by the producers, the Ente Nazionale Risi calculated a commercial availability of paddy rice equal to 1,255,077 tons, with a reduction of about 260 thousand tons (-16%). Furthermore, in year 2023 about 8,000 hectares less have been cultivated, which is the most significant area reduction ever recorded in the past thirty years. Thus, climate change continues to cause extensive damage to agriculture overall, with sudden and anomalous changes in temperatures and the alternative effects of floods and droughts, as recently witnessed in the late spring and initial summer weeks of 2023. With 1.5 million tons of rice a year, Italy covers 50% of the production of European Union, so it is easily understandable the amount of economic loss that the current situation has been causing.

Figure 26. Rice field affected by drought in northern Italy during campaign of 2022.

The situation is way more dramatic if we consider that in the previous year (2022), rice production had also collapsed due to meteorological instability. A condition of insecurity has thus arisen for farmers, who often are forced to abandon rice fields. An alarming situation indeed, because it will have effects on the ecosystem, the economy and the employment levels considering that rice also guarantees the environmental balance of entire territories.

During year 2022, according to the analysis led by the Institute of Atmospheric Sciences and Climate of the National Research Council (CNR-ISAC), based on recent data, 40% less rain fell in these areas compared to the historical average; also, snow levels were reduced by 35%. The vision offered by the Po River bed, dry and with well visible sandy banks during summer months, is dramatically representative of the condition of all other major rivers of Northern Italy, where most of the large lakes were below the level and the water potential of snow dramatically dropped (Figure 27).

Figure 27. The Po River bed in Emilia Romagna, near Parma, in June 2022.

Hence, drought is a major concern for food security, and new strategies for its prediction and preparedness need to be fostered and implemented. This is also why farmers and Research Institutions, together with major irrigation companies, are trying to experiment new strategies for production and adopt innovative agricultural management systems, with a special regard to irrigation and water use. Another example is offered by the experimental trials carried out by the Universities of Turin, Pavia and Milan, based on alternate agronomic and land management practices such as winter submersion. According to preliminary indications, a certain improvement of production can be achieved, as well as a significant reduction in emissions. Furthermore, an improvement in fertility can be obtained through the practice of green manuring, i.e. the use of the so-called cover crops. In this case, the technique foresees the sowing of a crop following rice harvest and its incorporation in the soil, before the cultivation of a new cropping cycle. The adoption of these strategies might also be beneficial in increasing biodiversity within the rice paddy environment, as these interventions might increase the presence of pollinating insects, amphibians and flora and fauna, especially aquatic birds.

4. Conclusions.

The increasing awareness regarding unsustainability of present agricultural methods and cultivation techniques on rice, coupled with the far more frequent impacts of climate change, have been recently fostering new research programmes. These are mainly focused on breeding for yield stability and grain quality, for cold and disease resistance as well as for salt tolerance, on the introduction of innovative weed control techniques and new biotechnologies. Some of the encouraging results obtained might well lead the way to unprecedented levels of results for Italian rice, especially important under the economic point of view, considering quality and quantity of its productions. In addition, recent studies' experiences based on different strategies especially regarding water management, conceived in order to save water and focused on drip irrigation, on the one hand; to reduce the depth of water table at the beginning of the irrigation season (i.e., winter flooding), on the other, are still in progress. The aim is to cope with increasing erraticism in distribution of rainfall and unpredictability of water availability, thus enabling higher resilience of the crop. Preliminary experimental results seem to be quite promising, as well as, very importantly, seems to be encouraging the general positive attitude farmers have shown towards the adoption of different approaches in water management, and within the traditional paddy rice areas. Looking at the future, a certain degree of optimism can be shared, despite the criticalities and the uncertainties linked to present climate change scenarios. A positive impact could derive from organic rice cultivation, possibly coupled with drip irrigation and innovative mulching, as this new form of approach could represent a way ahead for its undoubtedly positive effects on environment, landscape, and economics. Precisely for this reason, it is absolutely necessary that all actors involved in the field of rice production keep on sharing their experiences and knowledge, experimenting new techniques and opening new paths to innovation.

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SMALL-SCALE HYDROPOWER GENERATION AS PART OF THE MULTIFUNCTIONALITY OF AGRICULTURAL WATER JAPAN'S PRESENT SITUATION

Dr. Koji Inosako[1]

ABSTRACT

In Japan, agricultural water accounts for about 65% of the total available water resources. Agricultural water is used not only for crop production, but also for diverse other purposes such as fire fighting, snow removal in rural areas, ecosystem conservation, aquatic habitat maintenance, and groundwater recharge. These are understood as the multifunctionalities of agricultural water in Japan. In recent years, small-scale hydropower generation projects using agricultural facilities such as agricultural ditches and dams have been increasing, supported by the policy of the Japanese government and local governments to promote power generation using renewable energy. In this report, small-scale hydropower generation in agricultural facilities is considered as a new multifunctionality of agricultural water, and its potential and the current status in Japan are introduced.

Keywords: Renewable energy; Agricultural ditch; Feed-in Tariff Scheme for Renewable Energy in Japan

1. Introduction

In Japan, the theoretical maximum amount of available water resources for human use is approximately 410 billion m^3, about 83.5 billion m^3 of which is actually used every year. 54.4 billion m^3 is allocated as agricultural water, 11.6 billion m^3 as industrial water, and 15.4 billion m^3 as domestic water. Most of the agricultural water (94%) is used to irrigate paddy fields.

Agricultural water is also used for such diverse applications as crop production, fire fighting, snow removal in rural areas, ecosystem conservation, aquatic habitat maintenance, and groundwater recharging. These are the ordinary multifunctionalities of agricultural water in Japan. Agricultural water can also be used as a resource for hydropower generation. Hydropower generation is becoming a significant use for agricultural water. In this paper, I discuss small-scale hydropower generation as a new functionality of agricultural water and examine its present situation in Japan.

2. Significance of introducing small-scale hydropower generation using agricultural water

2.1 Power generation in Japan

Figure 1 shows a ratio of power generation in Japan from 1952 to 2019 (Agency for Natural Resources and Energy, 2023). In 2010, thermal power was 65.4% of total electricity, atomic power was 25.1%, ordinary hydropower exceeding 1000 kW was 7.3%, and new powers were only 2.2%. New powers include photovoltaics, wind, geothermal, biomass power generation, and small-scale hydropower less than 1000 kW. On the other hand, thermal power was 75.7% of total electricity, atomic power was 6.2%, hydropower was 7.8%, and new powers were 10.3% in 2023. Figure 1 shows that thermal power generation remains the main source of power generation in Japan. However, it simultaneously produces carbon dioxide (CO_2) and, in 2020, Japan's CO_2 emission corresponded to 3.2% of the world's output. That amount must be lowered to reduce global warming. Atomic power generation was expected to play a central role for this purpose. Therefore, the ratio of the atomic power generation to total electricity was

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gradually increased from 1952 to 2011. However, it has been very small since 2012 because the government temporarily shut down all nuclear power plants following the 2011 Tsunami and the Great East Japan Earthquake.

Resuming operation at these stations may take quite some time to ensure safety. Electric companies are increasing the thermal power generation to compensate for electric power shortage caused by the decline in atomic power generation, presenting a dilemma due to the resulting increase in CO_2 emissions. Thus, promoting electric power generation by non-fossil fuels should be considered as a countermeasure.

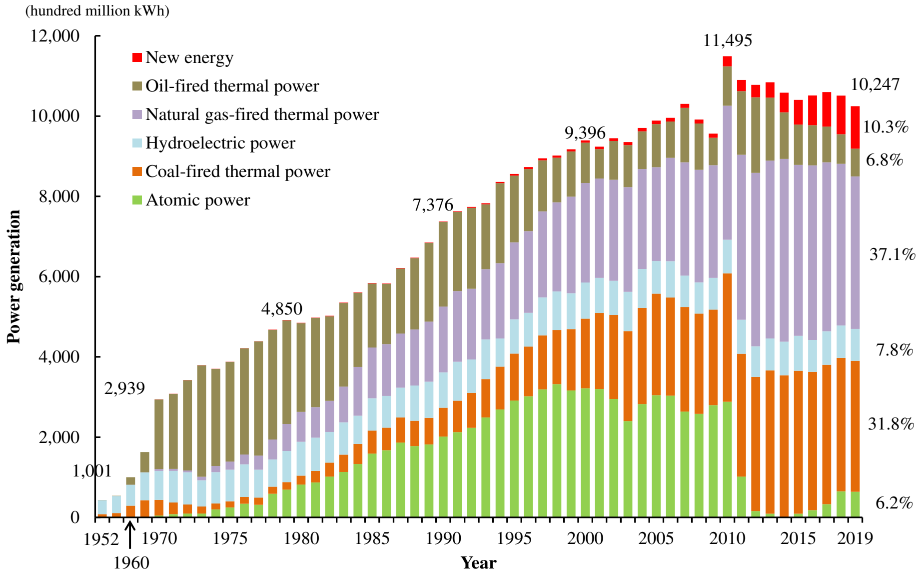


Figure 1. Fluctuation of power generation in Japan from 1952 to 2019 [This figure has been recreated from the original (Agency for Natural Resources and Energy, 2023) by the author]

Even though new sources of power have been consistently developed since the 1970s, mainstream power generation from these new sources does not yet exist. However, in 2003, the Japanese government began to promote new power by enacting the Renewable Portfolio Standard (RPS) system which forced electric companies to use a certain amount of electricity from new energy and enabled individuals or groups to sell renewable power to electric companies[2].

On July 1, 2012, the Japanese government passed the Feed-in Tariff Scheme for Renewable Energy in Japan (FIT), which superseded the RPS system. FIT requires electric companies to buy renewable electric power at a constant price that exceeds normal cost over a period determined in the contract between sellers and buyers (25 years for small-scale hydropower generation). Since electric company cost increases are simply passed on to consumers, the companies have no risk. This act might strongly promote the individual and group generation of renewable power.

2.2 Background of reassessment of hydropower generation

The Japanese government promotes renewable electric power generation for two reasons. One is that renewable energy does not directly emit carbon dioxide. The other is to increase energy self-sufficiency, which is very low in Japan and has been decreasing year by year. In 1960, self-sufficient energies of coal-fired thermal power and ordinary hydropower, occupied 57% of total power generation; however, by 2006, it fell to 4% because coal production was

[2] In Japan, the Electric Business Act mandates that electric power can only be sold to electric companies.

reduced drastically and oil importation increased. Since such renewable energy sources as solar, wind, and hydropower are widely distributed all over Japan, the utilization of new energy will increase energy self-sufficiency.

The contribution of hydropower generation is especially large because Japan has rich water resources. Compared with photovoltaics and wind, hydropower can stably generate electricity for 24 hours. A photovoltaic system does not work at night and its output energy is very small on cloudy days. Wind power generation is very irregular and stops during excessively strong or weak winds. Thus, hydropower generation has been reassessed as a useful option for electrical production.

2.3 Potentiality of small-scale hydropower generation using agricultural water

Categorization on the scale of hydropower generation slightly varies by country. In Japan, the New Energy and Industrial Technology Development Organization (NEDO) proposed classification categories (Table 1). The threshold of small-scale hydropower generation is 1,000 kW under Japanese law. The mini and micro hydropowers in Table 1 correspond to small-scale hydropower. Large, medium, and small hydropowers are grouped as ordinary hydropower generation. In this paper, hydropower generation less than 1,000 kW is called small-scale hydropower generation.

Table 1 Category of hydropower generations (NEDO, 2011)

Category	Scale
Large hydropower	> 100,000 kW
Medium hydropower	100,000 kW ~ 10,000 kW
Small hydropower	10,000 kW ~ 1,000 kW
Mini hydropower	1,000 kW ~ 100 kW
Micro hydropower	100 kW >

The majority of ordinary hydropower generation plants are greater than 1,000 kW. Since suitable sites for these plants have already been developed, ordinary plant construction decreases year by year. On the other hand, suitable sites for small-scale hydropower generation remain, and the development potential is promising (Matsumoto et al., 2013). In addition, recent technological developments enable the use of agricultural channels and irrigation ponds or agricultural dams for small-scale hydropower generation. Thus, the prospects for small-scale hydropower generation remains favorable.

Japan already has vast agricultural water facilities. The total length of the agricultural channels is 400,000 km (Figure 2) and the number of agricultural dams is almost 400 (Figure 3). Most of the channels and dams are not being used for hydropower generation.

When electricity is generated using these facilities, plant construction does not impact the environment. Furthermore, using these facilities for hydropower generation enables local production for the local consumption of electric power. In this case, the generated electric power is directly supplied to in situ facilities in rural areas.

The Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF) subsidizes the construction of small-scale hydropower generation plants as agricultural and rural development projects. 26 districts constructed plants from 1987 to 2007, and generation reached 0.103 billion kWh/year, which equals the amount of energy annually consumed by 25,000 households. The number of facilities rapidly increased after FIT launched and reached 109 in 2017. Generation was 0.181 billion kWh/year, which equals the amount of energy annually consumed by 60,000 households. Figure 4 shows the cumulative number of small-scale hydropower generation plants and the amount of removed CO_2, where the reduction ratio of CO_2 by hydropower generation was estimated to be 0.551 kg/kWh. CO_2 removal reached 100,000 t/year in 2017.

Undeveloped hydropower using irrigation water ditches and dams was estimated at 0.585 billion kWh/year (Agency for Natural Resources and Energy, 2008). Small-scale hydropower generation has the potential to generate enough energy for approximately 140,000 households every year. If all available sites for small-scale hydropower generation are developed, there will be a potential reduction of more than 300,000 tons of CO_2 per year.

Figure 2 Irrigation channel (Tottori pref. 2011)

Figure 3 Agricultural dam (Oita pref. 2011)

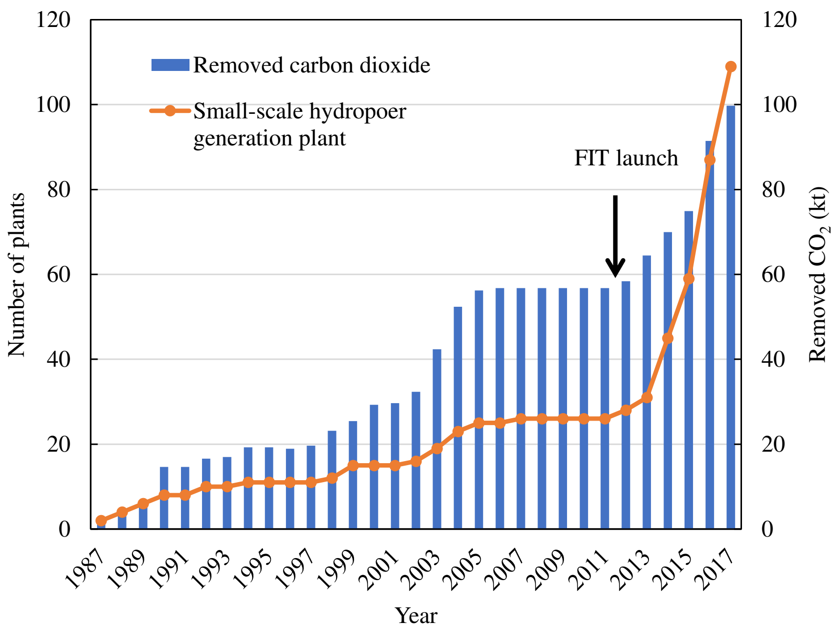


Figure 4 Time variation of cumulative number of districts and amount CO_2 removal.
This figure has been recreated from the original (Inotani and Kitamura, 2019) by the author.

3. Technical information about small-scale hydropower generation

3.1 Theory of output power and electrical energy

Water moves from high to low in total potential energy (potential energy + kinetic energy). When a turbine is put into a stream, the stream's energy rotates the turbine and initiates a spin force that drives the generator and creates electricity (Figure 5). The output power primarily depends on the force's severity.

Theoretical output power is expressed as follows:

$$P = ghQ \tag{1}$$

where P is the output power (kW), g is the acceleration of gravity (9.81 m/s^2), h is an effective head (m), and Q is the flow (m^3/s). The electrical energy (P_t, kWh) for t hours is

$$P_t = ghQt \quad (2)$$

The actual electrical energy is expressed using conversion efficiencies:

$$P_t = ghQt\eta_t\eta_g \quad (3)$$

where η_t and η_g are the conversion efficiencies of a turbine and a generator, respectively.

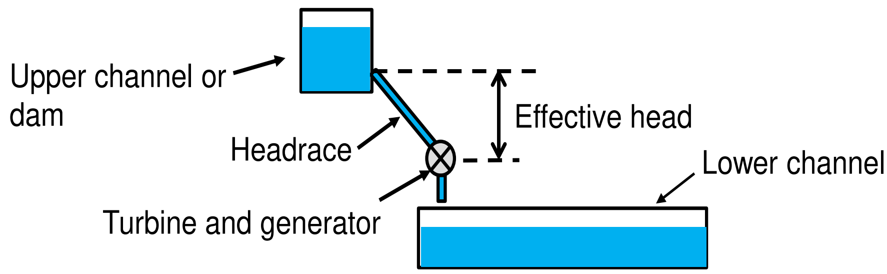


Figure 5 Concept of hydropower generation

When the water head at the generation plant is very small (Figure 6), output power and electrical energy can be estimated by Eqs. (4) and (5):

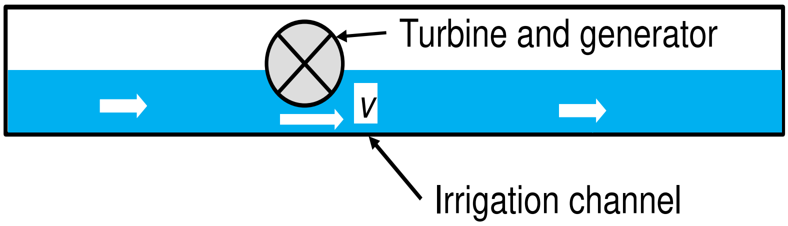


Figure 6 Hydropower generation in irrigation channel with very small water head

$$P = \frac{Qv^2}{2} \quad (4)$$

where *v* is the velocity of the water flow in an irrigation channel (m/s). The actual electrical energy (P_t , kWh) for *t* hours is

$$P_t = \frac{Qv^2}{2}t\eta_t\eta_g \quad (5)$$

The approximate values of the conversion efficiencies of turbines and generators are given in Table 2. Because these efficiencies become larger with an increase in output power, small-scale hydropower generation has lower efficiency than ordinary generation. Improving both efficiencies for small-scale hydropower generation is an important challenge.

Table 2 Approximate values of conversion efficiencies of turbines and generators (Itsumi, 2007)

Efficiency (%) / Output power (kW)	Turbine efficiency η_t	Generator efficiency η_g
2 ~ around 50	70 ~ 73	85
around 500	80 ~ 84	91
around 1,000	82 ~ 85	92
around 2,000	83 ~ 86	94
around 5,000	84 ~ 87	95

3.2 Turbine for small-scale hydropower generation

Since the hydropower generation discussed in this paper produces a small amount of energy, candidate sites include areas where ordinary plants cannot be constructed. Therefore, it is important for planners of small-scale hydropower generation projects to know the types and features of the available turbines. Turbines for hydropower generation are roughly categorized into three groups: impulse turbines, reaction turbines, and gravity water wheels.

Figure 7 shows a schematic view of the Pelton wheel, which is as an example of an impulse turbine. In this turbine, the water stream's velocity is maximized by converting the water's potential energy to kinetic energy before reaching the bucket. The water is spayed from a nozzle with a needle to turbine runners with bowl-shaped buckets to rotate the turbine. The force is regulated by the needle. This method is adequate for sites with high a water head and small flow. A cross-flow wheel is also a representative example of an impulse turbine (Figure 8).

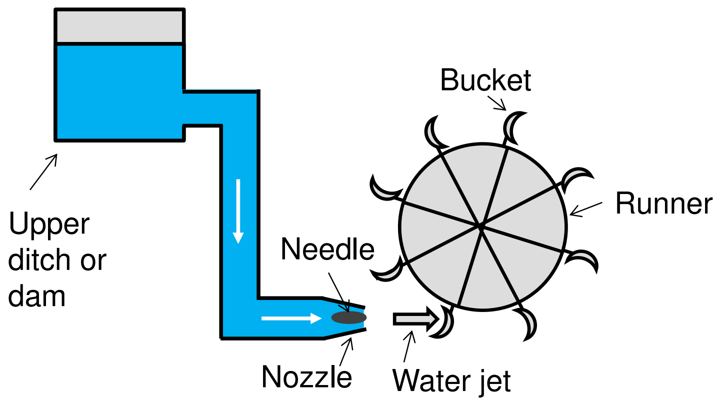


Figure 7 Schematic view of Pelton wheel

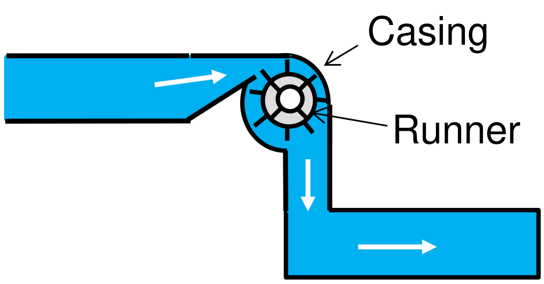


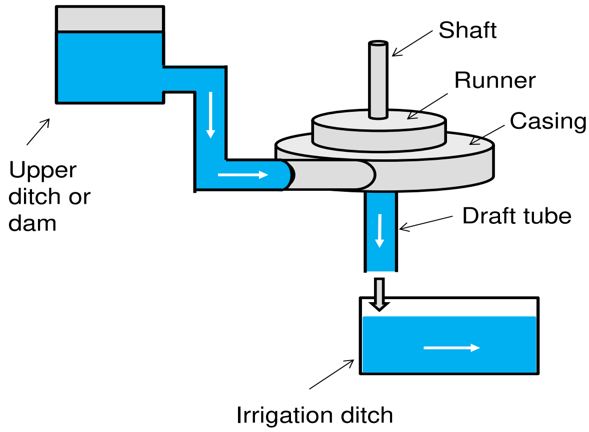
Figure 8 Schematic view of cross-flow wheel

Figure 9 shows a schematic view of a Francis turbine as a reaction turbine example of. This turbine draws a water stream into a casing (Figure 9(a)). The water passes through the runner vanes and flows out from a draft tube (Figure 9(b)). The runner is rotated by the reaction when the water passes between the vanes as the flow pressure pushes the vane out.

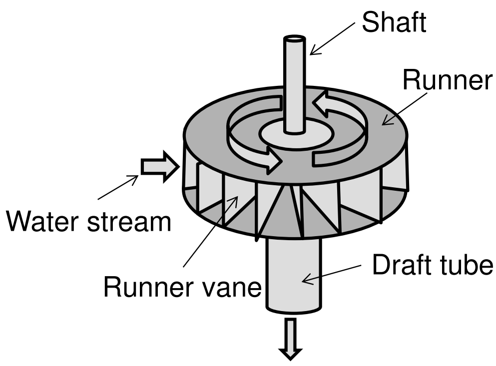
The Francis turbine is the most common in hydropower generation because it has high elasticity to various heads and flows and high energy conversion efficiency, which is advantageous for small-scale hydropower generation. One disadvantage is that the space between the runner vanes becomes clogged with dirt easily.

A tubular turbine, which is a type of propeller turbine, also uses the same concept (Figure 10(a)). A tubular turbine with a curved draft tube is called an S-type tubular turbine (Figure 10(b)). Generally speaking, reaction turbines are applied to the middle level of the water head.

Gravity water wheels, which have been around for more than 2000 years, are used at places with less than 5 m of water head. Originally, they mainly served as hydropower machinery for agricultural work. Recently, they have been adapted for small-scale hydropower generation systems. Figure 11 outlines an undershot water wheel as an example of a gravity turbine that is rotated by water mass. Since the rotation number per unit time is very small, we must increase it by a speed-up gear to generate electricity. An overshot water wheel and a screw turbine (Figure 12) belong to the same category. These turbines have the following features: lower cleaning maintenance because clogging from dirt seldom occurs, high turbine efficiency, and a larger structure than other turbines.

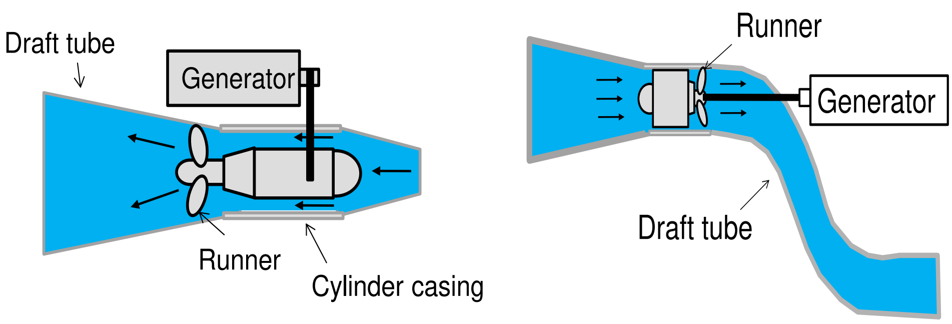


(a) Entire picture



(b) Runner configuration

Figure 9 Schematic view of Francis turbine



(a) Tubular turbine

(b) S-type tubular turbine

Figure 10 Schematic view of tubular turbine

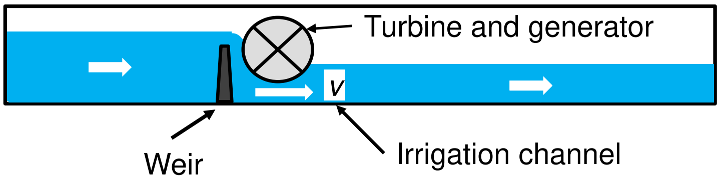


Figure 11 Schematic view of undershot water wheel

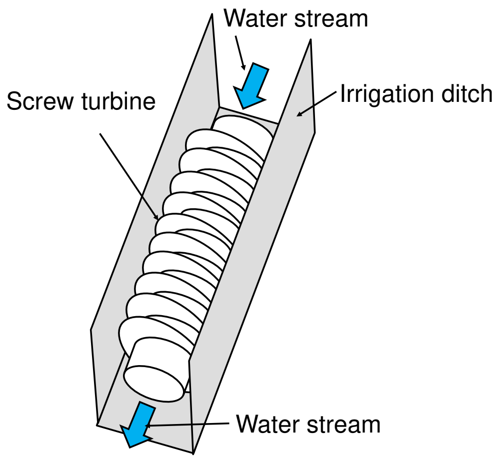


Figure 12 Schematic view of screw turbine

An example of the relationship among output energy, effective head, and flow is shown in Figure 13. This relationship is very convenient for hydropower generation planners. For example, when an effective head ranges from 2 to 10 m and the flow ranges from 0.05 to 0.4 m^3/s, a horizontal shaft propeller turbine is adequate for the site. When the head is 10 m and the flow is 3 m^3/s, we can select a cross-flow turbine or a vertical shaft tubular turbine. There are no applicable turbines for a range of less than 2 m in the water head. If it is in an open channel, we can use a gravity water wheel.

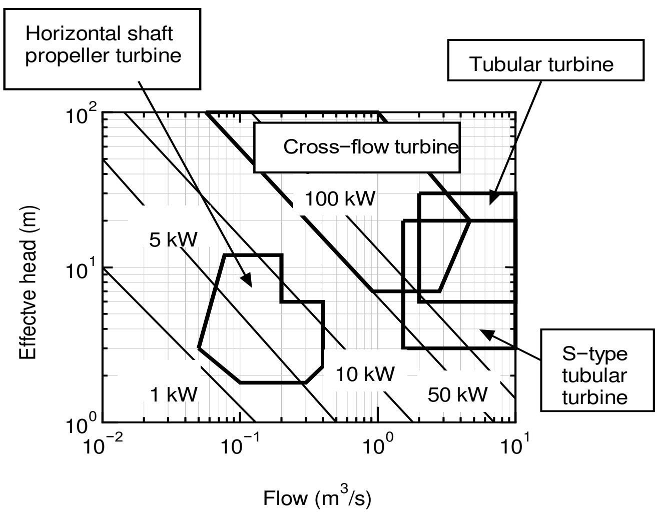


Figure 13 Relationship among types of turbines, effective head, and flow
This figure has been recreated from the original (Itsumi, 2007) by the author.

3.3 Generation system using agricultural ditches and dams

Some hydropower generation systems use agricultural ditches and dams. Figure 14 shows an outline of a dam-type power station that generates electricity using different elevations between water intake points in a dam reservoir and a power plant. Since it is the most common type of hydropower generation system, it is adopted not only for small-scale hydropower generation but also for ordinary scale generation. Multipurpose dams (water supply, irrigation power generation, and so on) or strictly irrigation dams are used for small-scale hydropower generation.

Irrigation channels are critical sites for small-scale hydropower generation using agricultural water. Figure 15 outlines a channel-type power station. The system is roughly categorized into two groups. One uses the difference in elevation between the upper and lower sides of the chute part in the main channel; water is withdrawn at the upper side into a branch channel where it flows to the hydropower plant. A headrace pipe is sometimes used instead of an open branch channel. The other group uses a hydraulic drop; a turbine is directly settled into a channel and rotated by the water falling down from the drop. Because these generation scales and plant sizes are very small, they can be applied to many sites.

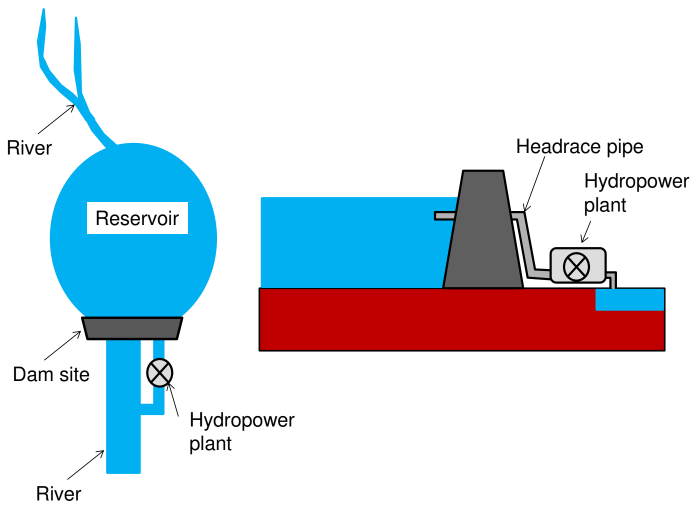


Figure 14 Dam-type power station

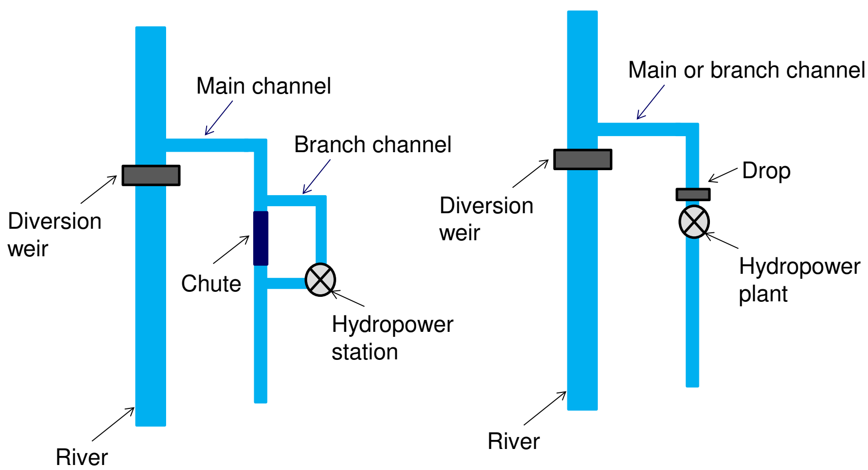


Figure 15 Channel-type power station

An irrigation pond is an agricultural facility used for hydropower generation. Its outline is shown in Figure 16. The basic concept for electricity generation is almost the same as the dam-type power station. However, the size and scale are smaller. An external headrace pipe such as an intake siphon is needed to generate power because there are no facilities for it. Irrigation dams have sluice gates on the levee body and the stored water is sent to the irrigation channel through the gate. It can be used for generating power instead of an external headrace pipe, but the water head must be small.

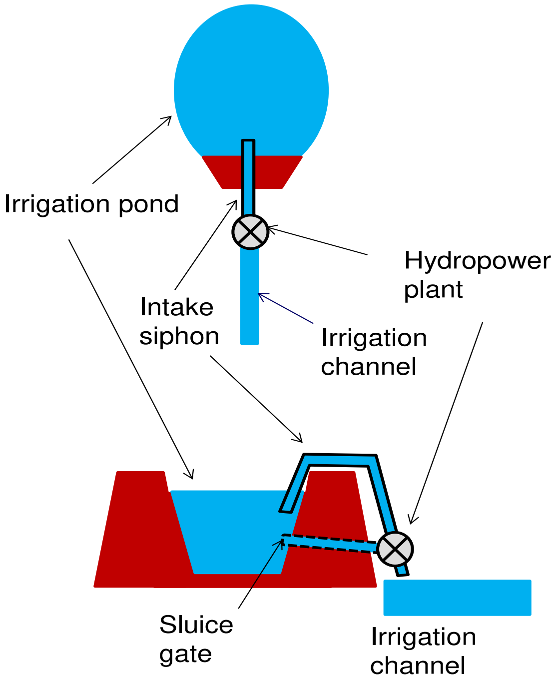


Figure 16 Irrigation pond-type power station

When hydropower generation is conducted with river water, water rights must be obtained. Water rights are controlled by Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT). MLIT also controls the water rights of agricultural water withdrawn from a river. Farmers only have water rights for agricultural management. Water rights for hydropower generation must also be obtained; therefore, farmers need to negotiate with MLIT to generate hydropower using agricultural water from rivers. If an irrigation pond is isolated from a river, its water is not controlled by MLIT. In most cases, the irrigation pond and the stored water are controlled by a land improvement district (LID), which is a corporation consisting of mainly farmers.

LIDs can generate hydropower using agricultural water in irrigation ponds without permission from MLIT. This is an advantage for the promotion of small-scale hydropower generation projects because negotiations with MLIT are sometimes problematic. Nevertheless, small-scale hydropower generation using agricultural water is primarily conducted at dam- or channel-type power stations. At present, an irrigation pond-type power technology is being studied (Fukatsu et al. 2011, Kusaka et al., 2012) but only a few hydropower plants at irrigation ponds have been constructed.

4. Case study

4.1 Prior case of local area projects in Japan

Recently, MAFF has begun subsidizing projects that generate electricity using agricultural ditches and dams. The main promoters are LIDs. However, some LIDs began working on these projects before public organizations started to provide financial support. Pioneers of this project include those in Oita Prefecture on Kyushu Island in western Japan (Figure 17).

The first project called the Fujio-iro Daiichi Plant, located in the rural area of Bungo-Ono City in Oita Prefecture, has been generating electricity since 1914. Fujio-iro is a 16-km irrigation channel that runs through the mountainous areas of Oita Prefecture, where, agricultural water was originally very scarce. Thus, its leaders privately developed an irrigation channel and constructed a small hydropower generation plant because the electric company was not able to send electricity to their mountainous area.

This plant had an effective head of 25.5 m and output power of 200 kW. It was refurbished in 1977 at a cost of about 65 million JPY (1 US $ equals 146.41 JPY in 2023 August 27). Its maximum output power was increased to 380 kW, and its annual power generation was 2.5 million kWh. Its maximum amount of intake water is 2.0 m^3/s. This plant uses a horizontal shaft Francis turbine.

Figure 17 Oita Prefecture

The second plant, the Fujio-iro Daini Plant, was constructed in 1984. It is larger than the Fujio-iro Daiichi Plant. Its effective head is 96.6 m, its maximum output energy is 1,500 kW, its annual power generation is 10 million kWh, its maximum amount of intake water is 2.0 m^3/s, and its construction cost was about 768 million JPY. It has the same turbine as the Fujio-iro Daiichi plant.

Funds for the construction and repair costs of these plants was borrowed by the LID because, at that time, local and central governments were not allowed to financially support developers.

The third plant is the Onobaru Hydropower Generation Plant, constructed in 1987 in rural Bungo-Ono City. It was the first to be supported by MAFF's land improvement project. Its maximum intake water is 0.3 m^3/s, its effective head is 117.4 m, its maximum output power is 260 kW, its annual power generation is 0.85 million kWh, and its construction cost was 213 million JPY. Although its effective head is the greatest, its output power is the smallest.

The fourth plant, the Haseo-iro Hydropower Generation Plant, has been operating since 1990. Its maximum intake water is 1.0 m3/s, its effective head is 173.4 m, its maximum output power is 1,300 kW, its annual power generation is 6.5 million kWh, and its construction cost was 641 million JPY. 15% of this cost was provided by MLIT but the remaining 85% was borrowed by the Haseo-iro LID.

These four plants generate about 20 million kWh of total electricity. That amount equals about 11,020 t/year of CO_2 and the annual energy consumption of about 4,800 households. All of the electricity generated at these plants is sold to electric companies. Table 3 shows the units of electricity sold by contract to electric companies and the income.

Table 3 Units of sold electricity and estimated income

Plant	Unit (JPY/kWh)	Output energy (kWh/year)	Estimated income (JPY/year)
Fujio-iro Daiichi	9.6	2.5 million	24 million
Fujio-iro Daini	9.6	10 million	96 million
Onobaru	11.2	0.85 million	9.52 million
Haseo-iro	9.2	6.5 million	59.8 million

The annual income of Fujio-iro LID is estimated about 120 million JPY. LID members in these areas usually pay dues of 100,000 JPY/ha. However, the Fujio-iro LID dues were reduced by 80% to 20,000 JPY/ha because it is generating income from electricity. Farmers benefit from hydropower generation using agricultural water.

4.2 Kibaru-iro hydropower station

The hydropower stations introduced in Section 4.1 are categorized into small or mini in Table 1. Since there are many small unused agricultural ditches and dams in rural and/or mountain areas, the micro hydropower plants in Table 1 should be installed in them. As an example, I introduce the Kibaru-iro Hydropower Station.

This plant was installed in the Kibaru-iro agricultural channel, which runs through the mountain area of Takeda City in Oita Prefecture and withdraws water at the Kanda diversion weir from the Kujyu River (Figure 18).

Figure 18 Kanda diversion weir at the source of the Kibaru-iro irrigation channel

This micro hydropower generation plant, constructed 3.1-km downstream from the weir in 2010, is managed by the Kibaru-iro LID. Its maximum output power is 25 kW. It is the first such small-scale plant on Kyushu, thus resembling a pilot project. The project’s objectives are: 1) to clarify the various problems arising from the operation of micro-scale hydropower generation at small channels; 2) to decrease the cost of agricultural products in mountainous regions by the self-support of agricultural electric power; 3) to engage the community by applying electricity to a shop that sells locally grown agricultural products; and 4) to demonstrate the contribution of rural areas to a low carbon society.

Figure 19 shows a schematic of this project’s entire layout. Water is taken from the inlet gate in the irrigation channel, where it flows down in a headrace pipe made from PVC to the outlet gate. A hydropower turbine and an electric generator are installed at the end of the headrace pipe. A vertical shaft propeller turbine and a permanent-magnet synchronous generator are adopted for obtaining 25 kW of maximum output power.

The difference in elevation between the inlet and outlet gates is 8.88 m, and the effective head for hydropower generation is 7.99 m. The annual power generation is 150,670 kWh, which equals the annual energy consumption of 36 households, but government regulations prohibit the power from being supplied to households (Electric Business Act). Thus, 5 kW of the electric power is conveyed to greenhouses and used to grow strawberries. The remaining 20 kW is sold to the electric company.

Figures 20 to 25 show aspects of the Kibaru-iro hydropower generation station. The inlet exists on a slope at an elevation of 8.8 m from the lowest point (Figure 20(a)). The water in the channel rapidly falls below the inlet (Figure 20(b)).

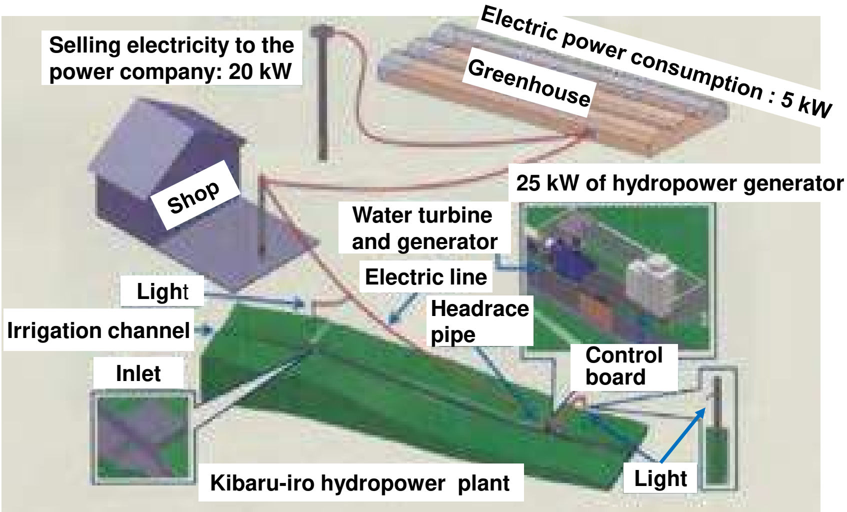
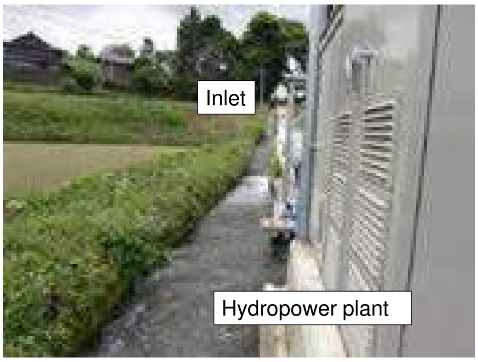


Figure 19 Schematic view of Kibaru-iro hydropower generation project



(a) Inlet on the upper side

(b) Chute below inlet

Figure 20 Kibaru-iro channel from the lowest poin

Figure 21 Aspect of channel near inlet

Figure 22 Upstream side from inlet

The inlet is on the channel's left side behind a board (Figure 21) that does not touch the channel's bottom, which prevent leaves and branches from entering the headrace pipe. This alleviates the serious problem of waste flowing into the turbines. In addition to the board on the inlet's front, a trap screen for such waste is located upstream of the inlet point. The LID managers manually remove the trapped waste every morning and evening. Although an automatic debris-proof device could be installed, it would increase construction costs. Because no reasonable debris-proof device exists for a small-scale hydropower generation station, this remains a substantial burden for station maintenance.

The water taken into the inlet is conveyed in a headrace to a hydropower plant. The headrace pipe is buried in the sloping road with an adequate gradient. Figure 23 shows a turbine and an electric generator, which is put over the turbine. Adoption of a vertical shaft propeller turbine reduced the needed floor space.

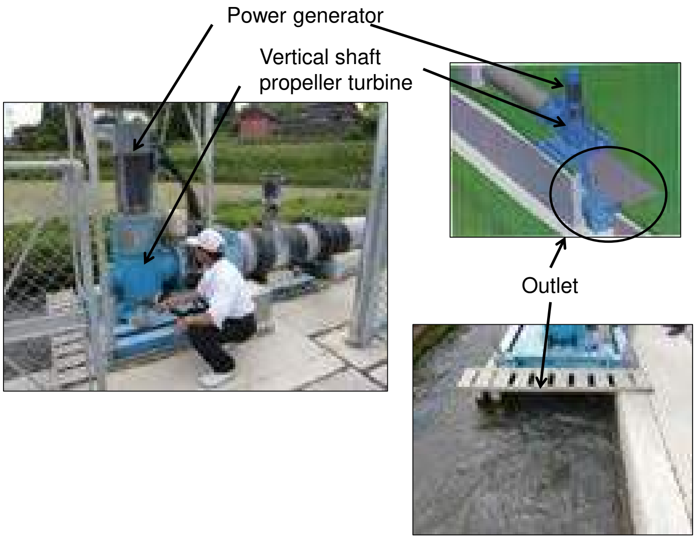


Figure 23 Turbine and electric generator

Figure 24 shows the electric flow of this power station. The generated electricity is conveyed to a distribution board. 20% of the generated power (5 kW) is consumed by the greenhouse, and the remaining 80% (20 kW) is sold to the electric company. The unit price of sold electric power was 8.2 JPY/kWh and the LID's income was estimated annually 1.2 million JPY in 2010.

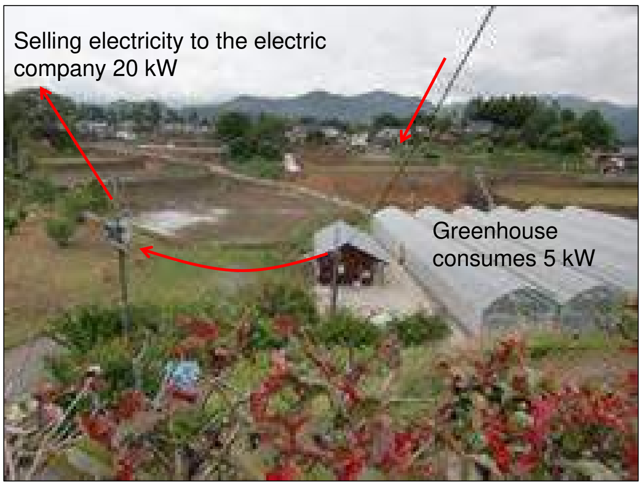


Figure 24 Electric flow

The various costs for this project are summarized in Table 4

Table 4 Costs of Kibaru-iro micro hydropower generation project

Construction costs	
Construction fee	50 million JPY
Output energy	150,670 kWh/year
Unit price of construction	332 JPY/kWh
Maintenance costs	
Maintenance fee	1.2 million JPY/year
Sold energy	144,643 kWh/year
Unit price of sold electric power selling	8.2 JPY/kWh*

*The unit price was contracted with the Kyushu electric company in 2010.

The unit price of sold electric power was determined by negotiations with electric companies based on maintenance fees and the amount of sold energy. As of 2010, since the LID gains little profit from this project, it did not recoup its construction costs. The subventions from MAFF and Oita Prefecture are 50% and 25% of the construction fee, respectively. The remaining 25% is paid by the Kibaru-iro Land Improvement District and is the LID’s liability.

FIT was enacted in July 1, 2012. This law fixed the unit price of sold electric power for output power less than 200 kW at 34 JPY/kWh for 20 years. In this case, the gross income is estimated about 4.9 million JPY/year, and the net income is 3.7 million JPY/year. However, actual income in 2021 was only 2.4 million JPY/year. This is because the amount of sold electric power decreased to 64,579 kWh/year. Nevertheless, this income is about twice as much as in 2010. In 2021, maintenance cost was only 0.8 million JPY/year, so the net income was even greater than in 2010. In LIDs, membership fees from member farmers cover the costs of maintaining land improvement facilities and operating the LIDs. The economic burden on farmers is reduced by allocating the costs of electric power selling from small-scale hydroelectric power generation to these expenses. FIT has thus become a driving force to promote small-scale hydropower generation.

5. Future prospects

The development of small-scale hydropower generation using agricultural water remains quite primitive in Japan. However, adequate technology for generating power continues to develop, and the amount of central and local government subsidies is increasing. Moreover, laws for promoting small-scale hydropower generation, such as FIT, are being enacted. MLIT has proposed easing the regulations on water rights for hydropower generation. These factors all contribute to the increasing promotion of small-scale hydropower generation with agricultural water in Japan.

In this paper, I described the possibility of small-scale hydropower generation using agricultural water and the current situation in Japan. The beneficial use of renewable energy is an important worldwide challenge. Agricultural water is an important resource for hydropower generation. Small-scale hydropower generation is a critical function of agricultural water and a new multi-functional use for it.

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EFFICIENT USE OF WATER IN CROP PRODUCTION IN INDIA

Dr K Yella Reddy[1]

ABSTRACT

This article deals about the need and importance of water allocation for crop production. Population growth has led to dwindling per capita water resources and to intensifying competition over scarce water resources. Water resources development and management are the key areas of focus for susstainable development of any region. Appropriate water policies at national, regional and local levels are important for proper allocation and distribution of water based on the priorities and set goals. Performance evaluation of irrigation projects on continuous basis is necessary to understand the reasons for lower efficiencies and to make improvements. Promotion of water saving crop production technologies and large-scale implementation of micro irrigation will help in improving the water use and the productivity. Examples of Indian context are shared in this article.

Keywords: Water Scarcity, Water Policy, Irrigation System, Water Use Efficiency

1. Introduction

Next to air, the other important requirement for human life to exist is water. It is the Nature's free gift to the human race. The use of water by man, plants and animals is universal. As a matter of fact, every living soul requires water for its survival. Although water is apparently abundant on Earth, only 2.53% (35 million km^3) of it is fresh water. The remaining 97.5% (1,3400million km^3) is salt water. Of the small amount of freshwater, only one third is easily available for human consumption, the large majority being locked up in glaciers and snow cover.

1.1 Water Scarcity

Imbalances between availability and demand, the degradation of groundwater and surface water quality, inter-sectoral competition, inter-regional and international conflicts, all bring water issues to the fore. The world and more importantly the developing countries are heading towards water stress and scarcity. They are left with no alternative but to adopt modern irrigation technologies, which save water, double the area under irrigation, improve yields and quality as well as save on labour, energy and crop production costs. Most countries in the Near East and North Africa suffer from acute water scarcity, as do countries such as Mexico, Pakistan, South Africa, and large parts of China and India. Irrigated agriculture, which demands bulk of the water in these countries, is also usually the first sector affected by water shortage, resulting in a decreased capacity to maintain per capita food production while meeting water needs for domestic, industrial and environmental purposes. In order to sustain their needs, these countries need to focus on the efficient use of all water sources (groundwater, surface water and rainfall) and on water allocation strategies that maximize the economic and social returns to limited water resources, and at the same time enhance the water productivity of all sectors.

Increasing population and higher levels of human activities, including effluent disposals to surface and groundwater sources, have made sustainable management of water resources a very complex task throughout the world. In addition, per capita demand for water in most countries is steadily increasing as more and more people achieve higher standards of living and as lifestyles are changing rapidly. Estimates show that with current population growth and water management practices, the world will face a 40 % shortfall between forecast demand and available supply of water by 2030 (Ijsbrand H. De Jong, 2020). Population growth has led to

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dwindling per capita water resources and to intensifying competition over scarce water resources. Table 1 shows the population growth, annual renewable freshwater available and per capita for selected countries.

Table 1. Population and per capita water availability for selected countries

Country	Population, Millions			Fresh water, km^3	Per capita fresh water, 1000 m^3		
	1994	2025	2050		1994	2025	2050
Brazil	150.1	230.3	264.3	6950	46.30	30.18	26.30
Canada	29.1	38.3	39.9	2901	99.69	75.74	72.70
China	1190.9	1526.1	1606.0	2800	2.35	1.83	1.74
Indonesia	189.9	275.6	318.8	2530	13.32	9.17	7.94
USA	260.6	331.2	349.0	2478	9.51	7.48	7.10
Bangladesh	117.8	196.1	238.5	2357	20.00	12.02	9.88
India	913.6	1392.1	1639.1	2085	2.28	1.50	1.27
Argentina	34.2	46.1	53.1	994	29.06	21.56	18.71
Japan	124.8	121.6	110.0	547	4.38	4.50	4.97
Turkey	60.8	90.9	106.3	203	3.34	2.23	1.91
UK	58.1	61.5	61.6	120	2.07	1.95	1.95
Egypt	57.6	97.3	117.4	59	1.02	0.60	0.50

1.2 Growing Water Demands

Water is intrinsic to our lives and to the ecosystems on which we all depend. Water is essential to life in every way, we need clean water for drinking, adequate water for sanitation and hygiene, sufficient water for food and industrial production, and much of our energy generation relies on or affects water supplies. Demographic and urban growth over the next century will mean a far greater demand for water for industrial production. Competition between users, and sectors, is therefore becoming increasingly important. The world's water usage pattern in the previous century, which is growing at alarming rate, is shown in Fig 1.

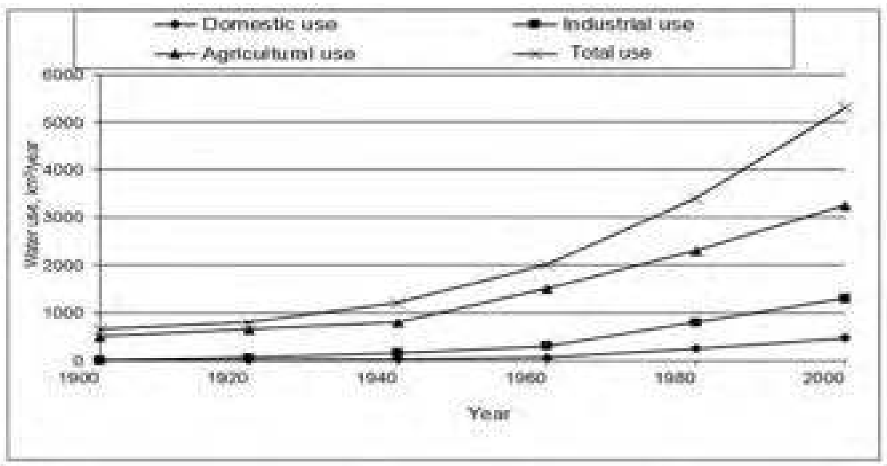

Figure 1. World's water use pattern in 20th century

2 Water for Agriculture

Today, not only water security, but also food security is facing a high level of risk. The water plays important role in the agriculture, manufacture of essential commodities, generation of electricity, transportation, recreation, industrial activities, etc. Almost 70% of all available freshwater is used for agriculture. With population growth and rising affluence, the need for food and thus agricultural water for irrigation is increasing. At the same time the quantity of water with a sufficient quality is declining. There is also an increasing demand to shift more of the water used in agriculture to higher-value urban and industrial uses. Thus, producing more with less is the only option. Water efficiency in agriculture has been extensively researched for many years. Universally applicable solutions are however difficult to come by, particularly due to different contexts and high specificity of agricultural practices. But efficiency gains are often possible through suitable crop selection, proper irrigation scheduling, effective irrigation techniques, and using alternative sources of water for irrigation. It should be noted that increasing water efficiency often provides benefits that go far beyond reduced water use.

2.1 Global Demands

For the last half-century, agriculture's principal challenge has been raising land productivity-getting more crops out of each hectare of land. As we have advanced into the twenty first century, the new frontier is boosting water productivity getting more from every liter of water devoted to crop production**.** More than half of the water removed from rivers and aquifers for irrigated agriculture never benefits crops. Because water performs many functions as it travels through the landscape toward the sea, however, it is important to think systematically about where water goes once it comes under human management.

It takes an enormous amount of water to produce crops: three cubic meters to yield just one kilogram of rice, and 1,000 tons of water to produce just one ton of grain (Biswas, 2001) and in agricultural use has increased by 12% since the 1960s to about 1.5 billion hectares. Current global withdrawals for irrigation are estimated at about 2,000 to 2,560km³ per year. Over-pumping of groundwater to meet agricultural water demand worldwide exceeds natural replenishment by at least 160 billion cubic meters a year.

The importance of agricultural water withdrawal is highly dependent on both climate and the place of agriculture in the economy. Figure 2 shows the water withdrawal ratios by continent, where the agricultural part varies from more than 80 percent in Africa and Asia to just over 20 percent in Europe.

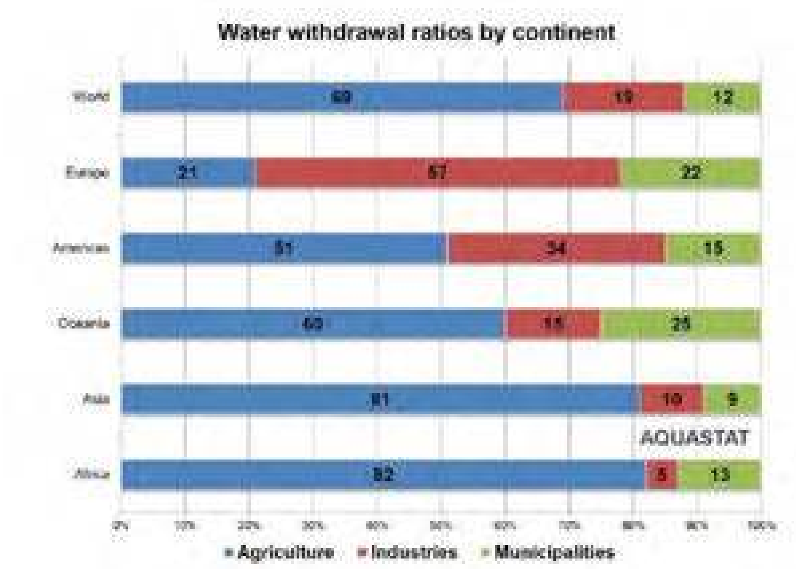

Figure 2. Continental wise water withdrawal ratios for important uses (auastat.fao.org)

Amount of water required for agricultural requirement in the future, based on the historical trends and food requirements estimated by FAO as shown in the Figure 3.

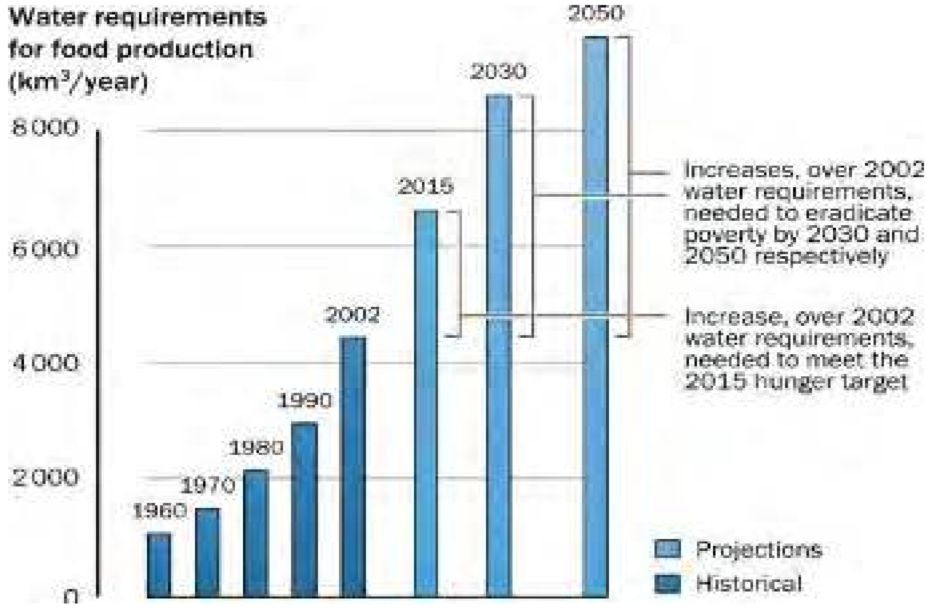

Figure 3. Growing water demands for agriculture (fao.org)

3 Losses in Irrigation System

The relative quantities of water being lost in irrigation systems at the different levels need to be looked at carefully. The largest volume of water being lost is usually at the field level where the wetted surface area is high and percolation below the root zone is also high. This is particularly the case where rice is grown with ponded water. The next largest volume of water lost is at the on-farm level, where water is distributed field-to-field or through field channels. The management losses are high at this level, as are the seepage losses as the ratio of discharge to wetted perimeter is low. Relative to these losses the seepage losses in the main canal network are relatively small, but the management losses can be high if the irrigation scheduling or the level of control and management is poor.

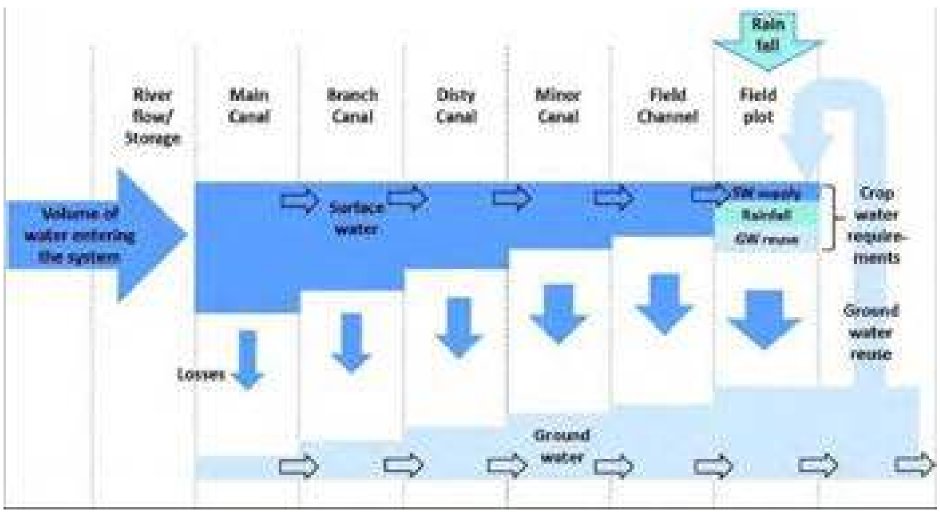

Figure 4. Linkage between different water sources in an irrigation distribution network

Additional area where significant water savings can be made is in active management of rainwater, either by rainwater harvesting on field plots or by allowing for rainfall events in scheduling of irrigation water supplies. Rainwater harvesting can be particularly relevant where paddy is being grown, increasing bund heights to retain larger portions of rainfall events during Kharif (autumn) can make a significant contribution to conserving water in reservoir-fed systems, leaving more water available for a subsequent Rabi (spring) crop. Benchmarking relies on identifying the key processes which transform the inputs into the desired outputs and impacts (Figure 5).

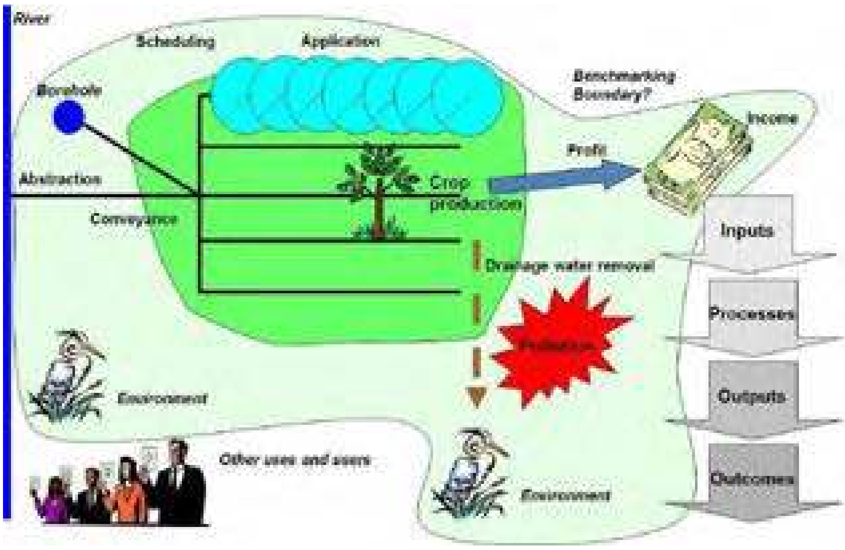

Figure 5. Identification of key processes in an irrigation and drainage scheme

3.1 Performance Evaluation

Assessment of performance of irrigation schemes on regular basis using standard Bench Marking process is very important for making needed improvements. The Central Water Commission (CWC), Govt of India, carried out Water Use Efficiency (WUE) studies for 30 Major and Medium Irrigation (MMI) schemes which were analyzed and reviewed (CWC,2010). Improving the performance of completed MMI schemes has been the main focus of the National Water Mission (NWM) and set a target of increasing the WUE by 20%. The assessment concluded (NWEISP, 2013) that:

(a) Nearly all the schemes are integrated in nature, with functions other than for irrigation;

(b) The current hydrological pattern of supply to the schemes varies from the original design conditions;

(c) There are concerns over dam safety due to lack of adequate maintenance;

(d) Excessive siltation of reservoirs has reduced their capacity and ability to supply the required volumes of water;

(e) Many of the medium and low storage volume reservoirs have a large surface area relative to their depth, resulting in high seepage and evaporation losses;

(f) In many cases the irrigation system is not able to supply the intended demands. This is due to a number of reasons, including non-availability of flows, inadequate capacity at the head-works, excessive losses (including unauthorized abstractions), inadequate capacity of canals, inadequate operating practices;

(g) In many cases there are problems with cross drainage – either due to the inadequate provision of cross-drainage infrastructure, or damaged or broken infrastructure;

(h) Control and regulation of irrigation flows is hampered by a lack of functioning control structures, including cross and head regulators;

(i) Discharge measurement is limited; I implementation of participatory irrigation management is often limited or non-existent;

(j) Rotation of water supplies, or Warab andi, is mainly limited to Punjab and Haryana, though Andhra Pradesh is re-introducing such practices;

(k) Actual cropping patterns vary from the design cropping patterns, resulting in a number of issues. These include head-enders growing more water intensive crops (than designed) resulting in inadequate availability at the tail-ends of schemes, and irrigation schedules based on design cropping patterns which fail to match actual needs;

(l) Irrigation from groundwater, ponds and tanks co-exists with the surface water irrigation system, and forms an important part of the farmers' decision-making on which crops to grow;

(m) In some cases where water scarcity exists scheme authorities have proposed diversification away from paddy to irrigated dry crops without assessing the impact on farmers' livelihood;

3.2 Core Areas of Priority

As a result of analysis of these case studies, and other reports the study concluded that there were six core areas requiring priority attention for improving water use efficiency in these irrigation schemes, these are summarized in Table 2.

Table 2. Core areas requiring priority attention

Core area	Required action
Storage	Consistent and continuous efforts are required to improve the performance of storage facilities in order to enhance the availability of supplies to the irrigation schemes.
Conveyance	Improvements are required in the design and the management of the conveyance systems
On-farm application	On-farm and field irrigation practices need to be improved in order to increase crop production and water use efficiency
Participatory efforts	Beneficiaries need to play an increasing role in the management of the systems
Crop management	A variety of actions are required to improve WUE, including crop diversification, low water use crops, better farm management, micro-irrigation systems and provision of quality inputs
Research and development (R&D)	Further R&D is required into water auditing, scheme monitoring and evaluation and benchmarking

In the CWC summary report (CWC, 2010), the results of the studies for each scheme are summarized and an overall summary is provided of the common reasons for low water use efficiency and common recommendations for improvement (Table 3).

Table 3. Common reasons and recommendations for low WUE from studies of 30 irrigation systems (CWC, 2010)

Common reasons for low WUE	Common recommendations for improvement of WUE
(a) Damaged structures (b) Silting in the canal system (c) Poor maintenance (d) Weed growth in the canal system (e) Seepage in the system (f) Over-irrigation (g) Illiterate farmers (h) Changing the cropping pattern	(a) Rehabilitation and restoration of damaged/silted canal system (b) Proper and timely maintenance of the system Selective lining of the canal and distribution system (c) Realistic and scientific system operation (d) Revision of cropping pattern, if needed (e) Restoration/provision of appropriate control structures (f) Efficient and reliable communication system (g) Reliable and accurate water measuring system (h) Conjunctive use of ground and surface water (i) Regular revision of water rate, Encouragement for formation of Water Users' Association (j) Training of farmers (k) Micro-credit facilities (l) Agricultural extension services (m) Encouragement of farmers for raising livestock

4 Water Policy

Water Policy for any nation is a very important requirement for proper allocation and efficient water utilization across all the sectors. The National Water Policy (NWP, 2010 and NWM. 2011) thus takes cognizance of the situation and has sketched a framework of creation of a system of laws and institutions and has drawn a plan of action considering water as a unified resource.

(a) Priority on use of water

NWP recognized the need for different water uses and suggests optimized utilizations for diverse use for which awareness on water as a scarce resource should be fostered. Governance institutions must ensure access to a minimum quantity of potable water for essential health and hygiene to all its citizens at their household. Ecological needs should be determined through scientific studies and a portion of water in rivers should be kept aside to meet ecological requirements. Regulated use of ground water should also consider contribution of base-flow to the river during dry periods through regulated ground water use.

(b) NWP on impact of climate change

NWP recognizes the importance of adaptation to the impacts of climate change by the community through resilient technologies and endorses adaptation to strategies on increasing storages, demand management, stakeholder's participation, and paradigm shift in design of river valley projects in coping with strategies to mitigate the impacts of climate change.

(c) Enhancing water availability for different use

The availability of water should be periodically and scientifically reviewed and reassessed in various basins every five years considering changing trends in climate change and accounted for in the planning process. Integrated watershed development activities with groundwater perspectives need be adopted to enhance soil moisture, reduce sediment yield, and increase overall land use productivity of rural development schemes.

(d) Demand management

The policy recommends evolution of a system of benchmarks for water uses for different uses, water footprints, and water auditing to promote and incentivize efficient use of water with clear emphasis on improving 'project' and 'basin' water use efficiencies through appropriate water balance and water accounting studies. Institutional arrangements for promotion, regulation and evolving mechanisms for efficient use of water at basin/sub-basin level need be established. Project appraisal and environmental impact assessment for water uses to inter-alia include:

(i) analysis of water foot prints,

(ii) recycle and reuse including return flows to be a general norm,

(iii) incentivizing economic use of water to facilitate competition,

(iv) adaptation to water saving means in agriculture such as controlled cropping patterns in endowment with climate, micro irrigation, recycling canal seepage through planned conjunctive use,

(v) monitoring the performance and

(vi) reclamation of commands from water logging, salinity and alkalinity.

(e) Regulation of water prices

A water regulatory authority should be established in each state to fix and periodically review and regulate the water tariff system and charges according to the principles of NWP. Volumetric assessment and allocation, entitlement and distribution should be the criteria to ensure equity, efficiency and economic principles. Water User Associations (WUAs) need be given statutory powers to collect and retain a portion of water charges and reuse of recycled water should be incentivized.

(f) Project planning & implementation

The policy document recognizes the need for planning the water resources projects as per efficiency benchmarks to address the challenge of impeding climate change factors. The projects should incorporate social and environmental aspects in addition to the techno-economic aspects through consultative processes with governments, local bodies, project affected people, beneficiaries and stakeholders.

(g) Data base and information needs

The policy stresses the need for establishing a 'national water informatics center' to collect, collate and process all hydrologic and water related information and maintain all information in an open and transparent manner on a GIS platform.

(h) Capacity building, research and training needs

The NWP emphasizes on the need for continuous research and advancement of technology, implementing newer research findings, importance of water balance in spatial and temporal context, water auditing for projects and hydrological systems, bench marking and performance evaluation. The need for regular training of the manpower for skill in water management is also recognized.

The provisions of the new NWP are clearly endorsing the principles of Integrated Water Integrated Water Resources Management (IWRM) and suggesting that the framework for water planning, development and management should be clearly governed by these principles.

5 Measures for Improvement

There are wide ranges of issues constraining the performance of MMI schemes throughout the water supply chain from the watershed to the crop root zone. These issues cover several domains - technical, social, economic, legal, political and environmental – with solutions to specific issues requiring action in a mix of these domains.

Better management lies at the heart of any endeavors to improve the situation. Hitherto the government and the Irrigation Department have focused on the construction of new irrigation systems to increase much needed agricultural production and livelihood security for the rural community. With increasing pressure on available water supplies, there is a need to focus on better management of constructed irrigation and drainage schemes, making them more efficient and productive, particularly in relation to their water use.

Good management requires good information based on reliable and accurate data – there is a need for improved data collection, processing and analysis. These data need to be used by management to understand the performance of irrigation and drainage schemes and to improve such performance where it is found to be inadequate, with benchmarking being used to identify gaps between best practice and less well performing schemes. Emphasis shall be on the importance of performance assessment and benchmarking as a basic management tool, it provides understanding of current performance ("where we are now") with identification of desirable and achievable performance ("where do we want to be") and, through gap analysis, with actions required to achieve these desired levels of performance ("how we plan to get there"). Every project management shall consider the following points for sustainability of irrigation management.

5.1 Water Management under Scarce Conditions

The valuable management practices of each project during scarce water conditions need to be recorded. Lessons can be learnt from such experiences for dealing with water scarce situations. The state of Andhra Pradesh has managed scarce water situations in Godavari and Krishna delta successfully and also improved productivity. Rotational irrigation and reuses of drainage water were some of the initiatives.

5.2 Large Scale Implementation of Water Saving Technologies

Any measures made towards promotion/execution of methods towards improvement of land and water productivity need to be mapped and accounted. In Krishna Delta presently more than 1 lakh (hundred thousand) acre area is put under direct seeded rice cultivation annually (Deelstra, 2018). Sowing is done at the onset of monsoon and once canal water comes it is converted to wet cultivation. It is saving cost of cultivation by about US $ 150 per ha (@ INR 83 per USD) apart from early harvest etc.

5.3 Promotion of Micro Irrigation (MI) at large scale

National task force committee on MI identified 69 million ha areas is suitable for micro irrigation in India. Now time has come to expand micro irrigation into command areas to improve water use efficiency substantially and increase productivity.

5.4 Incentivizing Water Saving

Concepts like virtual water and water credits are to be introduced to create awareness on saving of water and encourage the farmers or agencies for contribution towards improved water use efficiency through some incentives.

5.6 Gross Productivity

Accurate estimation of productivity achieved in each irrigation project is to be recorded accurately and also to be analysed in terms of economic parameters. The economic value of the crop yields needs to be worked out. Comparison with other projects will help in understanding the contribution made.

5.7 Multiple Uses of Water and Economic Value

Irrigation projects are largely multipurpose projects serving different sectors. In order to understand the economic contribution of any project, it needs to be accurately mapped and estimated the water utilized in various sectors and their economic contribution for overall economy. FAO has developed a tool called Mapping systems and Services for Multiple Uses (MASSMUS) for evaluating Multiple Uses of Irrigation Projects.

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WATER USE IN PADDY RICE CULTIVATION IN INDIA

Yella Reddy Kaluvai[1], and Krishna Reddy Kakumanu[2]

ABSTRACT

Paddy rice cultivation in Asian countries is a significant activity and it consumes a substantial amount of water. The water requirement for Paddy rice cultivation depends on various factors like climate, soil type, rice variety and management practices. The soil type and management practices like direct seeded rice, alternate wetting and drying and system of rice intensification are widely published on the paddy rice water use. The focus of rice variety on the water use is meagre. Researchers are highly focused on the duration of the crop to overcome the climate impacts and reduce the resource use. But the water requirement varies from nursery, vegetative and reproductive phase, which need to be addressed for all the varieties. Efforts on scaling-up the more sustainable and water-efficient practices is essential in India. These include adoption of irrigation techniques and greater awareness of water conservation among farmers. The paper has presented these in detail with its impact. Sustainable water management in agriculture especially in Paddy rice is essential not only for food security but also for the long-term health of India's ecosystem and water resources.

Keywords: Direct seeded rice; Alternate wetting and drying; System of rice intensification; Rice varieties; Water use efficiency, Methane emissions

1. Introduction

Rice *(Oryza Sativa)*, the world's most important food crop for about four billion people plays a vital role in the food and livelihood security. The crop occupies a significant position in the culture and heritage of many Asian countries since vedic period (1500 – 500 BCE). Rice is grown globally, around 160 million hectares cultivated in diverse soils, from 1.8 m below mean sea level (MSL) (Kuttanad Below Sea Level Farming System (KBSFS), Kerala, India) to 900 m above MSL in the Himalayas. In tropical countries, rice production systems are irrigated and low land rainfed. Irrigated rice systems account for 78 and 55 percent of rice production and harvested rice area globally, respectively. Rice cultivation is mostly concentrated in alluvial floodplain tracts, delta regions and inland valleys.

The largest area for rice cultivation is in India, followed by China and Indonesia; China has the highest production, but Australia has the highest productivity. India grows rice in 46 Mha with production of 129 million tons (Mt) of milled rice and average productivity of 2.7 t/ha (FY 2021-22). Over the years, the area under rice has increased about 1.5 times, with the rise in the production by more than five times. With this, India has not only achieved self-sufficiency in rice but also produces surplus to export. The leading rice producing states are West Bengal, Uttar Pradesh, Punjab, Odisha, Andhra Pradesh, Bihar and Chhattisgarh.

The Green Revolution enabled many countries to increase their agricultural production. India has also increased the rice area and production significantly over the years. The area has been increased from 30 million hectares to 46 million ha from 1950 to 2021-22 and the production from 23 million tonnes to 129 million tonnes during the same period (Statistica, 2023). It is evident that India ranks first in the area with 26.3% of the world rice area during 2017 and second in rice production with 146 million tonnes after China. The productivity has also increased from 1740 kg/ha (in 1991) to 2722 kg/ha (in 2022). Nonetheless, the productivity is still lower than other countries like china (6686 kg/ha), Bangladesh (4219 Kg/ha) and Myanmar (4081 kg/ha) (Palanisami et al., 2019). The productivity varies from region to region or state to state based on the soil, climate and water resource availability. In India, the major ten rice producing states are West Bengal, Punjab, Uttar Pradesh, Andhra Pradesh, Bihar, Tamil Nadu, Odisha, Telangana, Assam, and Chhatisgarh (Indiastat, 2021a).

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Besides increasing the production, India has entered into a new era of input use. The usage of high-yielding varieties, fertilisers and plant protection chemicals has increased manifold particularly in irrigated agriculture. Almost 90 percent of the total world's rice is produced using irrigation and is estimated 15-20 million hectares of irrigated rice may suffer water scarcity by 2025 (IRRI 2021). In India, 60 per cent of the area was covered under irrigation during 2014-15 (Indiastat, 2021b). Evidence also show that the irrigated rice consumes about 43% of the world's irrigation water (Bouman et al. 2007a, IRRI 2023) and the total value of rice production in the world is more than US $ 150 billion per year (Shetty et al., 2013).

2. Water requirement for Paddy

Water requirement for a crop depends on evaporation, transpiration i.e. evapotranspiration (ET) and metabolic needs of the plant; all together known as consumptive use. In addition to ET, water requirement includes losses during the application of irrigation water in the field (percolation, seepage, and runoff) and water required for special operations such as land preparation, transplantation, leaching etc. Water requirement is therefore a demand of water, and the supply would consist of contribution from rainfall, irrigation water and soil profile that contributes from shallow water table.

In each crop, there are growth stages at which moisture stress leads to irrevocable yield loss. These stages are known as moisture sensitive periods. If irrigation water is available in sufficient quantities, irrigation is scheduled whenever soil moisture is depleted to critical moisture level. Under limited water supply conditions irrigation is scheduled at moisture sensitive stages and skipped at non-sensitive stages. In rice, panicle initiation and flowering are the moisture sensitive stages.

Scheduling irrigation at these stages improves the yield and quality of grain filling. Generally, water requirement for a rice crop varies between 1200 mm to 2500 mm depending on the soil texture, structure and profile conditions. In black soils (with high clay content) water permeability is less and keeps the soil moisture for long duration. In case of sandy loam soils the water permeability will be high and regular irrigation is needed. So the percolation losses will be very high. But the availability of irrigation water from canals depends on the climatic conditions and it has a significant impact on the availability of water resources and rice production.

Rice is the largest consumer of water, having the lowest water productivity among the food grain crops in India. Enhancement of water productivity is necessary to compensate the need of additional water withdrawals over the next 25 years in order to meet the additional food demand. The National Water Mission also set a goal to improve the water use efficiency (WUE) by 20 per cent during 2008 and enhance the availability of water during 2012 in its national water policies (Bharat and Dkhar, 2018).

Researchers are paying attention to improving the rice production through developing new varieties and efficient cultivation practices from long time (Shobha Rani et al., 2010; Meera et al., 2014; Deelstra et al., 2018; Palanisami et al., 2019). Therefore, the present paper discusses the available options in sustaining the rice production, productivity and improving the WUE through varietal development and water saving practices.

3. Rice varieties and its characteristics in India

Rice is the ancient crop being cultivated over 10,000 years and its genetic diversity exceeds that of other crops. There are several species available and most widely known and grown is Oryza sativa, which is also called Asian rice. Rice is grown in different eco-systems and range of soils under varying climatic conditions. In India more than 1200 varieties were released for different ecosystems over the years (NRRI, 2021). The varieties were developed to attain specific characters such as resistance to pest and diseases, long grains, colour, shape, taste, aroma, productivity, tolerance to stress (drought and flood), market price etc. The important varieties that are grown in major rice growing states of India and their characteristics or features are presented in Table 1.

Table 1: Important varieties grown in major rice growing states in India and their characteristics

Sl. No	State	Major Varieties	Characteristics
1	Andhra Pradesh / Telangana	• BPT 5204, NLR 9672, NLR 9674, MTU 7014 • IR 20, IR 36, Improved Samba Masuri • Vajram, Prathibha, Krishnaveni, Chaitanya • Rasi, MTU 17 • Vikas • Satya, Tella hamsa	• Resistant for Blast • Resistant to Bacterial Leaf blight • Resistant to Brown Plant Hopper • Drought tolerant • Saline tolerant • Cold tolerant
2	Assam	• Bahadur, Chandrama, Kushal, Manoharsali • Basundhara, Aghoni, BLuit, Chilarai • Basundhara, Satyaranjan, Manoharsali • Luit, Basundhara, Satyaranjan	• Resistant to Blast • Resistant to Bacterial Leaf blight • Resistant to Brown Plant Hopper • Resistant to Gall midge
3	Bihar	• Turata, Pranht, Richaria, Saroj, Dhan Laxmi, Saket-4, and Pusa 2-21 • RajendraSweta, Sita, Kanak, Santosh, Sujata, Rajshree, Rajendra Bhagwati, and IR 36 • Shakuntla, Satyam, Kishori, Pankaj, Radha, Rajendra Masuri-1, BPT 5204 & Swarna	• Short duration (70-120 days) • Medium duration (125-135 days) • Long duration (140-160 days)
4	Chhattisgarh	• Aditya, Heera, Annada, Danteshwari, Purva, Samleshwari • Abhaya, Mahamaya, Chandrahasini, Jaldubi • Aditya, Tulsi, Abhaya, IR 64, IR 36 • Mahamaya, Bamleswari • Taroari Basmati, Madhuri, Pusa Basmati 1	• Suitable to rainfed upland areas • Suitable to Gall midge areas • Suitable to Blast areas • Suitable to Blight areas • Fine scented rice
5	Odisha	• Bali • Laghu sarad, arad, Dalua • Bada Sarad	• Drought resistance • Resistant to pest and diseases • Resistant to early drought and flood
6	Punjab	• Palman 579, PR 115,Basmati 385 • PR 4141, PR 114, PR 116, PR 120, PAU 201, • Basmati 386, Super Basmati, Pusa Sugandh 2, Pnjab Basmati 2, Pusa 1121, Punjab Mehak 1 • PR 109, PR 110, PR-113, PR 115-118, PR 120	• Early maturity, • Long slender grain & good cooking quality • Extra-long grains, good cook quality with strong aroma • Bacterial blight resistant
7	Tamil Nadu	• IR-64, CO-47, ADT-36, ADT-37, ADT-43, ADT-45, ADT-47, ADT-48, ASD-16, ASD-17, ASD-20 and MDU-5 • IR 20, IR 36, CO 43, CO 46, ADT 38, ADT 39, ADT 46, Bhavani, MDU 3, MDU 4, TRY 1, ASD 19, TPS 2, TPS 3 and White Ponni • CR 1009, BPT 5204, ADT 44	• Short duration (resistant to blast, BPH, gall midge, etc) • Medium duration (Stem borer, BPH, BLB, saline & alkaline soils) • Long duration (stem borer, blast, BLB)

Sl. No	State	• Major Varieties	• Characteristics
8	Uttar Pradesh	• NDR 1045-2, Narendradhan 97, Shusk Samrat, Barani Deep, Nagina 22, Renu, Sudha etc • CSR-13, CSR-27, Narendra 2, Usar 1, Narendra Usar Dhan 2, 3, 2008 • Jitendra, Chakia 59, Jalnidhi, Barah, Avarodhi, Jal Lahari, Halmagan, Jalpriya • Kasturi, Vasumati, Pusa Basmati 1, Pusa Sugandh 2, Pusa Sugandh 3, Madhuri, etc	• Suitable to rainfed upland areas • Saline tolerant varieties • Semi-deep/deep water resistant varieties • Scented rice varieties
9	West Bengal	• Bhupen, Jaldi Dhan 13, 15, Jamini, Khanika, Kiron, Panke, PNR 519, Shatabdi • Ratna, Rasi, Suraksha, Sasyasree, Gontra Bidhan 1, CM 25, 31, Kunti, Kisan etc • CSR-10, 13, 27, CST 7-1, Lunishree, Jarava, Mohan etc • Amulya, Nalini, Jitnedra, Sudheer, Ambka, Bagheerathi, Bhudeb, Biraj,Golak, etc • PNR 546	• Suitable to rainfed upland • Resistant to blast • Saline tolerant varieties • Resistant to Semi-deep/deep water • Aromatic fine grain variety

Source: compiled from Meera et al. (2014), Shobha Rani et al. (2010) and TNAU (2021)

All the varieties are tested and released with the specification of the variety providing the duration of crop, stem length, panicle length, spikelet colour, grain length-width-weight, production etc. The breeding and agronomic trails specify the characteristics of the variety and management aspects related to the nutrient treatments (Sahu et al., 2017; Shankar et al., 2021), weed control (Rao, 2011), pest and disease management at different stages of the crop. To improve the water use efficiency and reach the goal of the national water mission the demand side from the crops with area covered and their varietal information on water requirement would help in improving the efficiency from supply side (NWM, 2021). The Government of India is also targeting the water budgeting at the Gram Panchayati (Village) level through water security plans and the interventions on managing water at various levels would be essential for demand and supply side management (Ministry of Jal Shakti, 2019; WDC-PMKSY, 2021).

4. Enhancing water productivity in rice through different practices

The major portion of water available in Indian River basins is used for irrigation of rice, making it the largest consumer. The conventional/traditional method of rice cultivation practiced so far is transplanting of rice seedlings in ponded water that ensures steady yields. But due to the growing climate uncertainty and insufficient irrigation water in the canal commands new management practices have to be adopted that can help in sustaining the rice production and ensure food security. The alternate methods that can be practiced to improve the water productivity in rice are: a) direct seeded rice, b) alternative wetting and drying, c) modified system of rice intensification, etc. The details of these practices in comparison with the normal irrigation method are as follows.

4.1 Direct Seeded Rice

The direct seeded rice (DSR) can be practiced through three methods viz., 1) dry seeding, 2) wet seeding and 3) water seeding by evading the nursery and transplantation (Joshi et al., 2013). In case of dry seeding, seeds are sown directly into dry soil at a depth of 2-3cm, immediately after the pre-monsoon showers. The method is suitable to rain-fed and irrigated environment with precise water control. In irrigated areas the dry seeded fields can be converted into wet method based on the availability of water from canals. Irrigation can be provided 45-60 days after sowing and then managed as a wet system. In wet seeding, pre-germinated seeds are broadcasted (scattering seeds by hand) or sown in the puddled soils. It is most favourable to rain-fed lowlands and irrigated areas with good drainage facilities. The wet method is practiced in Malaysia, Thailand, Vietnam, Philippines and Sri Lanka. Drum seeded rice is recommended in India using the wet method, where seeds are sown in line on the puddled soils. In water seeding method, seeds are broadcasted in standing water (5-10 cm) in areas where red rice or weed problem exists.

In the present study, the first dry seeded method was explained, which requires less water, labour, and has lower cultivation costs with comparatively equal or slightly higher grain yields than traditional transplanting paddy rice method (Yadav et al. 2011, Kakumanu et al. 2019). Raising seedlings in nursery for 30 days and subsequent transplanting in main field is not practiced. The land is prepared under dry conditions and hence puddling is not required. The rice seeds are directly sown into the soil manually or by machine operated seed drills at a depth of 2-3 cm below soil surface after the monsoon showers. The crop also matures 10 days earlier than the transplanted paddy rice. But the weed growth is higher in DSR and requires the use of selective pre- and post-emergence herbicides to address the problem. Timely sowing gives possibilities to take up a second pulse crop in time.

The validated field observations of DSR from Andhra Pradesh state under Krishna River Basin illustrate that the seed and sowing cost reduced by 68-77% when compared to the traditional transplantation method (Table 2). The variable cost also reduces significantly from INR 8000 to 15000 ($100 – 187) per hectare. This is mainly due to reduction in land preparation, raising nursery and transplantation costs. Only two labour man-days are sufficient in DSR, as compared to 25 man-days in the transplantation method. The water use recorded by Replogle-Bos-Clemmens (RBC)flumes show that there is an overall reduction of 2500 m^3 (11-23%) in water application. The yield difference between DSR and the transplantation method also ranged from 1-6 quintal/ha. The WUE, gross margins and cost benefit ratio over the years also depicted the benefits of the DSR. The irrigation cost includes both water charges (INR/ha) and operational cost for irrigation (labour). The scheduling of irrigation after 45 days of sowing has reduced the water use by 11-23%.

The DSR cultivation is picking pace with the development of improved varieties and availability of effective weedicides. The state governments are also providing seed drills for subsidy in upscaling of DSR practice. The Indian Council of Agricultural Research has conducted trails by using Rice-wheat seeder equipment for regulating the seed rate and sowing the seed at desired depth with a spacing of 8-15 cm within the row and 20 cm between the rows. The trails conducted at farmers' field show the yield gain of 3-16% under different varieties and reduced cost of cultivation by INR 10,450 ($ 130) per ha (ICAR, 2021).

Farmers' perceptions on DSR adoption also show positive response concerning the reduced labour, reduced cost, resistance to lodging of plant, increased number of tillers, reduced incidence of pests and diseases due to proper spacing with seed drill, deeper root system for absorbing the nutrients effectively, lower water demand in the initial crop growth stages and early crop maturity (Kakumanu et al., 2019; Kaur and Singh, 2017). Understanding the constraints in adopting DSR is also important to overcome the challenges. The weed problem in the initial phase of the crop, land levelling, specified depth in seed sowing, heavy rains immediately after seed sowing, poor drainage facilities and dropping of grains due to increased number of tillers and panicles need to be managed (Mahajan et al., 2013; Kakumanu et al., 2019; ICAR, 2021).

The impact of DSR adoption is seen at four folds such as improved water productivity, savings on fuel consumption, intensification of cropped area, additional revenue and reduced methane emissions. For example, reduction of water use by 23 per cent, additional income generated with the adoption of DSR in a district/state improves the revenue generated, the dry seed method skips the puddling process and saves about 25 litres of diesel/ha and CO_2 emissions (2.62 kg of CO_2 per litre), and reduced methane emission of 95 kgCH_4/ha (Joshi et al., 2013). At all growth stages of rice crop, DSR practice reduces the total methane emissions by 85-96 percent (Liu et al., 2022).

4.2 Alternate Wetting and Drying

Alternate Wetting and Drying (AWD) irrigation is a water management system where rice fields are not kept continuously submerged but are allowed to dry intermittently during the rice growing stage and water is applied after disappearance of flooded or ponded water (Borrell et al., 1997; Yamaji, 2011). In AWD, irrigation is provided when the water level drops to 5-15 cm below the soil surface (Pic 2). The number of days when the field is allowed to be non-flooded before the next irrigation is applied can vary from 1 day to more than 10 days, depending on the soil type and crop growth stage. AWD promotes better root growth, facilitates nutrient uptake and increases land and water productivity (Uphoff, 2006). AWD is also considered as a Climate Smart Agriculture (CSA) practice because it generates multiple benefits in terms of increased productivity by promoting more effective tillering and stronger root growth of rice plants (Bouman et al., 2007b; Liu et al., 2013; Richards and Sander; 2014), mitigates Green House Gases (GHGs) emissions, particularly methane (Jain et al., 2013),and enhances adaptation to water scarcity by consuming less irrigation water (Siopongco et al., 2013; Ishfaq et al., 2020). AWD can reduce methane emissions by up to 50% owing to the periodic aeration of soil that inhibits methane-producing bacteria (Jain et al., 2013).

Picture 1. Direct seeded ric

Table 2. DSR -Field observations

Particulars	Year 1		Year 2		Year 3		Year 4		Year 5	
	DSR	Tradi-tional	DSR	Tradi-tional	DSR	Tradi-tional	DSR	Tradi-tional	DSR	Tradi-tional
Nursery preparation (INR/ha)	0	1150	0	1423	0	1764	0	2282	0	3023
Main land preparation (INR/ha)	2200	5687	2400	5787	3825	5234	4762	5431	4357	9555
Seed & Sowing (INR/ha)	1540	6440	1540	6720	2348	8565	2852	8903	2315	7976
Manures & Fertilizers (INR/ha)	8000	7221	9000	8240	13274	16184	14794	17856	13198	13483

Particulars	Year 1		Year 2		Year 3		Year 4		Year 5	
	DSR	Traditional	DSR	Traditional	DSR	Traditional	DSR	Traditional	DSR	Traditional
Plant protection (INR/ha)	6011	6123	6214	6324	6678	9425	7254	9548	13559	13183
Cost of irrigation (INR/ha)	1000	899	1200	1000	1780	1155	1984	2108	1700	1700
Weeding (INR/ha)	4200	3576	4100	3765	2825	4210	7068	7750	4098	3262
Harvesting, Threshing, Winnowing & Transportation (INR/ha)	14721	14647	15732	15652	19179	17012	21824	21786	15950	15885
Interest on Variable Cost (IVC) (INR/ha)	589	715	628	764	780	993	946	1182	862	1064
Total Variable cost (INR/ha)	38261	46458	40814	49675	50689	64542	61484	76846	56040	69130
Land tax (INR/ha)	625	625	750	750	750	750	750	750	750	750
Land lease amount (INR/ha)	16456	16456	17000	17000	19320	20526	27900	27082	29716	29631
Interest on Fixed Cost (INR/ha)	285	285	296	296	335	355	478	464	508	506
Total Fixed cost (INR/ha)	17366	17366	18046	18046	20405	21631	29128	28295	30973	30887
Total Cost (INR/ha)	55626	63823	58860	67721	71093	86173	90611	105142	75540	88895
Yield (qt/ha) (INR/ha)	48	46	67	66	60	54	68	66	68	67
Price realisation (INR/qt)	1132	1132	1152	1152	1857	1857	1710	1710	1720	1720
Straw Yield (qt/ha)	198	204	208	215	212	217	210	213	212	222
Straw Price (INR/ha)	6000	6000	7000	7000	10000	10000	11000	11000	10000	10000
Gross returns (INR/ha)	59804	57676	84622	82606	121420	110278	127280	123860	127354	125491
Net returns (INR/ha)	4178	-6148	25762	14885	50327	24105	36669	18718	51814	36596
Production cost (INR/100Kg)	1170	1398	874	1032	1185	1596	1333	1593	1107	1324
Benefit Cost Ratio (INR/ha)	1.08	0.90	1.44	1.22	1.71	1.28	1.40	1.18	1.69	1.41
Water Utilised (m^3/ha) *	9950	12910	8680	11270	11090	13320	14680	16520	10790	13530
WP (kg/m^3) @	0.48	0.35	0.78	0.58	0.54	0.41	0.46	0.40	0.63	0.50

* Water data from field observations, n=50, @ Water Productivity (WP) is defined as the amount of produce obtained per unit of water used, 1 USD = 80 INR

Picture 2. Alternate Wetting and Drying of Rice

While attempting to reduce CH_4 emissions, there is however, a trade-off of increasing emission of N_2O from AWD fields when fields are heavily fertilized, but the net effect on the Global Warming Potential is reduced under AWD (Jain et al., 2013).

AWD can reduce the number of irrigations needed during the crop growing stages compared to the normal continuous irrigations and can lower irrigation water consumption by at least 25% (Borrell et al., 1997; Thiyagarajan & Biksham, 2013). Water savings in AWD compared with normal irrigations (NI) could be as high as 45%, thus resulting in reallocation of the saved water to downstream fields for irrigation or other purposes (Siopongco et al., 2013). Furthermore, AWD can save farmers money spent on pumping costs by using less irrigation water and reducing labour cost through improved field conditions thereby increased net return for farmers (Richards and Sander, 2014). AWD, therefore, generates multiple benefits related to GHG emissions reduction (mitigation), reducing water use (adaptation where water is scarce), increasing productivity and efficiency of water use for grain production (Borrell et al., 1997), contributing to food security (Bouman et al., 2007a), and controlling water-borne disease-causing organisms (Van der Hoek et al., 2001).

The validated field observations of two years data from Andhra Pradesh of Krishna River basin for Kharif (autumn/rainy) and Rabi (spring/dry) seasons show that water consumption under AWD is less than normal irrigation (NI) at all stages of the crop (Figure 1). The volume of water consumed during Rabi season by normal irrigation (2,901 m^3) is greater than AWD (1,802 m^3) at the panicle initiation to flowering stage. It is also higher during Kharif with NI (2251 m^3) and AWD (1569 m^3). In total, the NI rice consumed 25,281 m^3 water during Rabi and 17,234 m^3 of water in AWD, which saved about 32 per cent. Similarly, Kharif NI rice consumed 22,477m^3 water and AWD reduced the water use to 12,453 m^3, saving about 44 per cent of water. The water saved can be used to grow other supplementary food crops with short duration or reallocating to the downstream fields.

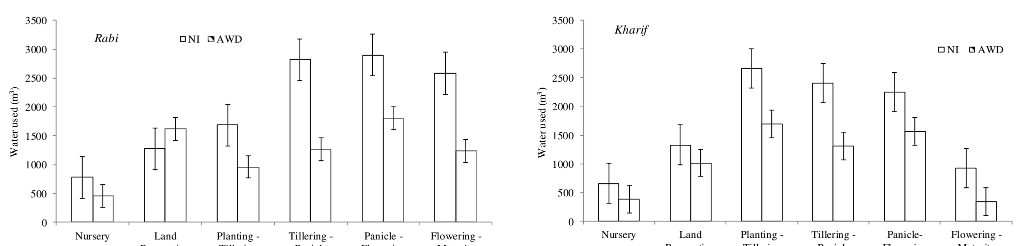

Figure 1: Water consumption at different growth stages of rice under AWD and NI during Rabi and Kharif season

The average rice yield under AWD is 7.4 tons/ha during Rabi and 5.59 tons/ha during Kharif which was higher than the NI (6.5 and 4.6 tons/ha during Rabi and Kharif, respectively). Except the number of grains per panicle, all the other yield components and grain yield are higher in Rabi season than Kharif in AWD as well as NI, probably due to more sunshine hours in Rabi and varietal differences (Table 3). AWD fields exhibited higher agronomic performance with respect to number of tillers, particularly at 65 Days After Transplantation (DAT), the number of panicles per hill, and grain yield during Rabi as well as Kharif seasons, compared to rice plants grown under the NI treatment.

Table 3. Growth and yield parameters of rice grown under NI and AWD fields during Rabi and Kharif season.

Parameters	Rabi (Variety MTU 1010)		Kharif (Variety BPT 5204)	
	NI (n=126)	AWD (n=126)	NI (n=207)	AWD (n=207)
Number of hills/m^2	30	30	24	22
Number of tillers	24	28	21	23
Number of panicles/hills	15	17	11	13
Panicle length (cm)	27	27	22	22
Number of grains/panicles	150	146	156	167
1000 grains weight (g)	25	25	19	20
Grain yield (ton/ha)	6.5	7.4	4.6	5.5

* Number of tillers recorded 65 DAT (Days After Transplanting).

The possible explanation for the higher agronomic performance of AWD in these studies could be:

- AWD improves the root system environment by allowing better access for oxygen and water absorption by the rice plant during the growing period;
- AWD improves the micro environment at the plant base and root zone which, in turn, reduces the conditions for pest and diseases incidence; and
- AWD enhances water and fertiliser use efficiency by reducing the water and nutrient losses via deep percolation and seepage. However, nitrogen losses may increase in AWD due to the multiple cycles of nitrification and denitrification, particularly if the application of fertiliser is not properly managed.

The water productivity of AWD also ranges from 0.40 to 0.48 kg/m^3/ha, which is almost 50% greater than the NI (0.21 to 0.26 kg/m^3/ha). Similar results have been found in other rice growing countries where water productivity is greater under AWD than NI, despite considerable variation among the sites (Table 4).

Table 4: AWD performance in water productivity during the rice growing period.

Country (site)	NI (kg/m^3)	AWD (kg/m^3)	References
Japan (Chiba)	1.30	1.70 (+31%)	Yamaji (2011)
Philippines (Muňoz)	1.20	1.48 (+23%)	Belder et al. (2004)
China (Tuanlin)	0.99	1.07 (+8%)	Belder et al. (2004)
Australia (Queensland[1])	0.65	0.66 (+2%)	Borrell et al. (1997)
Japan (Fukuoka)	0.50	0.76 (+52%)	Sujono et al (2011)
Australia (Queensland[2])	0.48	0.41 (-15%)	Borrell et al. (1997)
Philippines (Guimba)	0.25	0.46 (84%)	Tabbal et al. (2002)
India (Andhra Pradesh)	0.24	0.45 (+88%)	Kakumanu et al. (2016)

[1] Dry season; [2] Wet season. Percentages in brackets indicate positive/negative change by AWD over NI field.

The total methane emissions from NI fields were estimated to be 220 kg CH_4-C during Rabi from a small farmer land-holding size of 2 ha field. In the Kharif season, emissions from a big farmer land-holding size of 6 ha field were estimated to be 616 kg CH_4-C, assuming the default value of 11 g CH4-C /m^2 (Mitra, 1992). In contrast for AWD, the total estimated methane emissions were 44 kg CH_4-C in Rabi and 132 kg CH_4-C in Kharif, representing 20% of the emissions incurred under NI. However, these estimates appear too low for AWD when compared with measured data by Rajkishore et al. (2013) who found CH_4-C emission averages 37.7 kg/ha under System of Rice Intensification (SRI) in Tamil-Nadu, India.

The total CH_4 emissions and total CO_2 equivalents from AWD fields estimated in Andhra Pradesh state were much lower than the NI fields in Kharif and Rabi seasons (Table 5). Hence, AWD has potential to reduce the Global Warming Potential (GWP) by at least 1/3 of the NI rice field (IRRI, 2009). GWP is a measure of the total energy that a gas absorbs over a particular period (usually 100 years), compared to CO_2 equivalents.

Table 5. Estimated total CH_4-C emissions and CO_2 equivalent from NI and AWD rice fields during Rabi and Kharif seasons

Method / Season	**Rabi Seasons (n = 2 ha from small farmer holding)**		**Kharif Seasons (n = 6 ha from big farmer holding)**	
	kg CH_4-C	kg CO_2 equiv.	kg CH_4-C	kg CO_2 equiv.
NI	220	5500	660	16500
AWD	44	1100	132	3300

Note: Calculated using the global warming potential of CH_4 = 25 times of CO_2 in 100-year time horizon (IPCC, 2007).

There is considerable literature showing that methane emissions from AWD rice fields are comparatively lower than continuously flooded paddy fields (Sidhu & Benbi, 2011; Jain et al., 2013), supporting the lower estimated methane emissions from AWD compared with NI in the current study. The practice of AWD helps reduce methane emissions from rice soils due to the periodic removal of anaerobic conditions, thereby halting the production of CH_4. However, the alternating cycles of aerobic and anaerobic conditions may trigger substantial N_2O emissions as a result of bacterial conversion of other nitrogen compounds to N_2O, and its subsequent release from the soil.

AWD causes more N_2O emissions than the continuously flooded NI fields by creating nearly saturated soil conditions with increased soil redox potential, promoting N_2O production (Jain et al., 2013; Ali et al., 2013). Australian studies showed that while the soil of unflooded rice systems like AWD remained aerobic throughout the experiment as evidenced by Eh values in excess of 400 mV, the flooded treatments successively became weakly reducing (< 300 mV) upon flooding. Proper nitrogen management should, to some extent, curtail N_2O losses (Bhatia et al., 2010).

4.3 System of Rice Intensification/ Modified System of Rice Intensification

System of Rice Intensification (SRI) is a potential alternative to traditional way of flooded rice cultivation. SRI has shown great promise to address the problems of small amounts of quality seeds, water scarcity and labour saving in nursery. SRI was initiated in Madagascar in the 1980s by the French agronomist Father Henri de Laulanie and has been adopted by many farmers in more than 50 countries. It was introduced to India in 2000 in Tamil Nadu, Puduchery and Tripura (Thiyagarajan and Biksham, 2013).

SRI is a package of agronomic practices which exploits the genetic potential of rice plants, creates a better growing environment, enhances soil health, reduce inputs such as seeds, fertilisers, water, and labour requirement for planting. The practice consists of six key components such as land levelling, planting of less than 14 days old young single seedlings, square planting (25x25 cm), green manure application, alternate wetting and drying and cono-weeding (remove weeds between the rows of rice by cono weeder/machine). SRI could reduce CH_4 production by about 30-60 per cent and lower the global warming potential significantly (Jain et al., 2013; Rajkishore et al., 2013). In addition, SRI can reduce water consumption by 22 to 25 per cent compared to paddy rice.

Despite the favourable reports, SRI is highly criticized and could not get adopted at a wider scale due the challenges in the need of skilled labour for transplanting of young seedlings (< 14 days), marking of main field for transplantation and cono-weeding. It was also reported that SRI does not have any significant increase in yields and depends on soil and other environmental conditions, knowledge, and experience (McDonald et al., 2008). Research reports also make a case against the SRI, arguing that higher yields are due to the soil fertility associated with great nitrogen supplying ability (Tsujimoto et al., 2009).

Farmers are unable to follow all the key components and are modifying the practice as per their convenience (Palanisami et al., 2010). The scarcity of labour is also forcing many famers to adapt to farm mechanisation. Rice or machine transplanters have come into existence to overcome the scarcity of labour. Machine transplanters can reduce the labour scarcity and follow the SRI practice with specified spacing (Pic 3). Spacing between the rows can be adjusted and follow the components of SRI.

Hence, SRI is also named as modified system of rice intensification (MSRI). The seedlings are grown in trays with a medium containing soil, vermicompost, molasses-sugarcane by-product and major nutrients containing urea, phosphorus, and potassium. Seedlings will be ready for transplanting after 12-15 days after seeding. About 175-188 trays are required per hectare. The main field need to be puddle and levelled and drain the ponding water before transplantation.

The validated field observations on a pilot basis from Krishna River Basin of Andhra Pradesh show that the MSRI utilises 50 per cent less seed rate and labour (Table 6). The labour requirement for transplantation is heavily reduced in MSRI when compared to conventional practice and uniform spacing (25x16 cm) can be noticed for better tillering and panicles.

Picture 3. Machine transplantation of Rice

Table 6: Field observations of MSRI

No.	Item	Year 1		Year 2	
		Conventional	MSRI	Conventional	MSRI
1	Seed rate (kg/ha)	60-75	30-35	60-75	30-35
2	Days to transplant	30-35	15-18	30-35	15-18
3	Cost of nursery including seed (INR/ha)	10170	12500	10170	12500
4	Labour required for transplanting/ seeding operations	25	3	25	3
5	Spacing (cm)	30 X15 (Zigzag)	25 X16	30 X15 (Zigzag)	25 X16
6	No of hills/sq-meter	22	23.80	23.20	25
7	No of effective tillers/hill	11.20	12.10	15.10	15.60

No.	Item	Year 1		Year 2	
		Conventional	MSRI	Conventional	MSRI
8	No of grains/ panicle	121	119	121	123
9	Days to maturity	149	144	144	141
10	Water utilized (m^3)	15100	14900	12650	11280
11	Yield (kg/ha)	4584	5203	6411	7104
12	Water productivity (kg/m^3)	0.30	0.34	0.50	0.62
13	Total cost of cultivation (INR/ha)	40511	40559	45674	45712
14	Gross returns (INR/ha)	45618.42	51665.79	64110	71040
15	Gross margin (INR/ha)	5107.42	11106.79	18436	25328
16	Benefit cost ratio	1.12	1.27	1.40	1.55

The number of hills per sq.m and tillers in a hill are higher compared to the manual transplantation. The crop can resist lodging during heavy rains and flood conditions. The effective tillers in a hill range from 12-15 and increase the panicle grain number. The yield of rice found to be higher by 6-7 qt/ha compared to conventional/manual transplantation and there is no significant difference in cultivation cost. The gross margin and benefit cost ratio are also higher in MSRI practice.

The water scheduling can be alternate wetting and drying, but challenging under canal systems. The MSRI has reduced the water application and was able to save 785 m^3 on average. The WUE is also high in MSRI. The practice has also an additional advantage of early harvest and reduced methane emissions as presented in AWD method. The trials conducted in Tamil Nadu to compare SRI and conventional transplanting also show that there is 22 per cent water saving under SRI with additional yield gain of 18 qt/ha and additional water productivity of 0.26 kg/m^3 (Geethalakshmi et al., 2016). The methane flux is also lower than conventional practice during panicle initiation, heading and maturity stages. The nitrous oxide is slightly higher in SRI under panicle initiation stage (Geethalakshmi et al., 2016).

The major challenges in MSRI are, seedlings older than 18 days are not suitable for machine transplantation, requires lot of skills for raising seedlings in trays, land should be levelled and standing water should be drained before machine transplantation, machine transplant 4-6 seedlings per hill in some places instead of 2-3 seedlings, availability of machine transplanter on time for small farms and lack of awareness on practicing machine transplanters.

5. Climate Change Adaptation and Mitigation in Rice

The government of Andhra Pradesh, India has prepared the State level Action plan on Climate Change (SAPCC) to address existing and future risks and vulnerabilities. The challenges involved in water management are low irrigation efficiency (i.e., 40%) and water productivity (0.48 kg/m^3) in canal irrigated agro-eco systems. Good water management practices will increase yields, improve crop quality, conserve water, save energy, decrease fertilizer requirements, and reduce non-point source pollution. Timely information and knowledge are most critical to decide on the exact amount of water required by a crop in a given climatic condition and for effective design and management of irrigation system and irrigation scheduling.

ClimaAdapt Project, which was implemented during 2012-16 in Nagarjuna Sagar Project area of Krishna Basin, has tried to address some of these problems including climate change risk assessment and vulnerability mapping, and further identifying suitable climate smart adaptation measures, capacity building of men and women farmers and stake holders, and providing policy recommendations. Important initiatives were:

5.1 Climate Smart Rice Farming Systems

Various adaptation technologies related to water management for improving the on-farm water use efficiency were tested with the participation of men and women farmers and implemented under canal commands. Direct Seeding of Rice (DSR), Machine Transplantation of Rice (MSRI) and Alternate Wetting and Drying (AWD) were validated over 5 seasons and implemented in a systemic or cluster approach (adopted by a group of farmers).

For more accurate hydrological measurements, RBC flumes were used to monitor and measure water levels and discharges (Pic 4). This also helped to create awareness amongst farmers. The installed innovative low-cost sensors (CLICK and TWEET) developed by the ClimaAdapt program at distributary committee and water user association (WUA) level help in water budgeting and scheduling of irrigations according to the need of the crop (Pic 5).

5.2 Initiatives to risk minimization: weather-based crop insurance scheme (WBCIS)

The WBCIS is another issue of focus, expected to provide a significant way out to reduce vulnerability to weather risks in the agricultural sector. It is being tested and implemented in most of the states in India. But, its uptake by the farmers is poor due to lack of awareness, trust and quality of data from the weather stations. In the ClimaAdapt project, the challenges to implement WBCIS were analyzed involving farmers, private agriculture insurance companies and government agencies. Automatic weather stations were installed to overcome some of the constraints in developing customized weather index products.

Pic. 4. RBC flumes for Water Measurement

Pic 5. Use of sensors and ICT tools for efficient water management

5.3 Capacity Building of Farmers, Youth and School Children

A demand driven capacity building and knowledge dissemination is the need of the hour to increase the adaptation to climate change and up-scale the technologies. The community-based Village Knowledge Centers (VKCs) were established in two study sites and they demonstrated that effective use of communication technologies and timely information and knowledge to men and women farmers allowed then to take informed decisions to reduce risks and increase income. A large number of youth and school children were trained on various aspects of water measurement and management (Pic 6).

Picture 6. Youth and school children learning use of sensors for water measurement

5.4 Framework of up-scaling

Innovations from the ClimaAdapt project are now entering into the curricula of training institutions and methodologies for enhanced outreach are developed. Some of them, such as the soil moisture sensors, plant clinics and village knowledge centres can provide high quality services at an affordable cost provided they deliver services to farmers on demand. Based on the ClimaAdapt project experiences, a set of recommendations are provided for the state of Andhra Pradesh for large scale implementation of innovations and approaches successfully tested.

6. Conclusion & Recommendations

The climate change and its variability are expected to have a serious impact on the agriculture and water sectors affecting the food security and livelihoods of the rural population. The national water policy has recommended improving the water use efficiency by 20 per cent to overcome the scarcity and climate effects in the country. As rice is the major water consuming crop in the country, attention was given on adaptation strategies to improve the water productivity. The short duration varieties, drought and heat tolerant varieties were developed by the researchers but estimates on the water utilisation are lacking. The water saving practices like direct seeded rice, alternate wetting and drying, and system of rice intensification/modified system of rice intensification etc. are getting significant recognition in enhancing the water use efficiency, income of the farmers and reducing the methane emissions. Nonetheless, up-scaling of the practices is challenging due to the lack of proper technical knowledge and awareness among the farmers and incentives for improving water use efficiency.

Therefore, the present study recommends that the future research on varietal development release should also focus on water requirement under different agro-climatic conditions. The information would help the planners to estimate the supply and demand of water in the region as per the variety adopted. The water saving practices can be further disseminated and the database on adoption of water saving practices is essential at district, state and national level to estimate the benefits of it. Water measurements at the distributary level also help in allocation of allotted water as per the demand and any saving can be incentivised as additional area in the tail ends can be brought into cultivation.

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RICE CULTIVATION IN EGYPT

Zeinab Hussein BEHAIRY[1]

ABSTRACT

Rice (*Oryza sativa* L) is an edible starchy cereal grain and a grass plant (family Poaceae). Roughly one-half of the world population, including virtually all of East and Southeast Asia, is wholly dependent upon rice as a staple food.

Rice in Egypt is rated among the main important field crops after wheat and maize. This importance comes, for instance, because of its low cultivation costs, in comparison with other field crops such as maize and cotton, higher profitability compared to other summer crops, and its storability for long periods of time. Rice cultivation also helps limit seawater intrusion into the northern Nile Delta lands. Rice is successfully cultivated in northern Egypt, where the composition of the soil has high levels of salinity, which is not appropriate for many other crops. So, rice could be used also as a land reclamation crop to improve the productivity of this kind of soils. Moreover, rice is an important crop for export and could be an important source of foreign currency.

In Egypt, research in rice cultivation started 100 years ago. Significant advances were made over the last thirty years, after the establishment of the Rice Research and Training Center (RRTC) in 1987 in Kafr Elsheikh, in cooperation with the United States Agency for International Development (USAID) and the International Rice Research Institute (IRRI). The research center's activities include the following: 1**-** Breeding & variety production (Classic breeding, Biotechnology, Hybrid Rice), 2- Agronomy (Agriculture Practices, Irrigation and Plant physiology), 3- Seed varieties genes protection, 4- Technology transfer.

Egypt has now many highly stable yielding varieties of which most of them are tolerant to different abiotic stresses such as drought, salinity, and high temperature. Some of them are early maturing varieties (short growing season) saving about 30% irrigation water consumption every year. It is worth mentioning that the national average rice yield increased to about 9.5 tha^{-1} which is considered one of the highest averages worldwide. Despite the high productivity and the quality of Egyptian rice worldwide, its high-water needs, and Egypt's water scarcity, were reflected in the rice cultivation policy adopted by the Ministry of Water Resources and irrigation which is as follows:

February 2018: the Ministry of Water Resources and Irrigation decided to reduce the rice agriculture area in Egypt from 1,700,000 feddans***** (714 ha) to 724,200 feddans***** (304.088 ha) to rationalize water in Egypt. The decision identified nine governorates to cultivate rice; the nine governorates are: Kafr El-Sheikh, Sharqia, Damietta, Dakahlia, Beheira, Alexandria, Ismailia, Port Said and Gharbia and rice cultivation was prohibited in Upper Egypt, Suez, South Sinai, Marsa Matrouh, Qalioubiya, Menoufiya and Giza (the lower Nile valley). *(1 feddan = 0.42 ha)

In 2019, Egypt produced about 3.3 million tons, while the Egyptians' annual consumption of rice was estimated at 4.3 million tons; therefore, domestic production remained insufficient. For this deficit in production to be compensated, Egypt had to turn from an exporting country to become an importing country due to the water shortage crisis the country is suffering from.

The Ministry of Water Resources and Irrigation (MWRI) re-published the Ministerial Decree of the year 2020 indicating the Nile Delta provinces that would be planting rice in the year 2021. The allotted rice cultivated area for the year 2021 is set for 1,074,200 feddans (~451,164 ha) in nine governorates. The MWRI tended to increase the area of rice cultivation to provide a surplus for export, but the imports are still high.

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Lastly, it is important to refer to the Awards for Egyptian Researchers towards Irrigation Water Saving and Development of Rice Crop. Three researchers have received three awards, two from the International Commission of Irrigation and Drainage (ICID) in the years 2008 and 2016**,** the third prize was awarded by the Egyptian Ministry of Agriculture and Land Reclamation in 2022**.** However, what distinguishes the Egyptian rice varieties from the rest of the world is its high productivity per unit area. Rice is very sensitive to water deficit and consumes large quantities of water during its growing season. The main constraint of rice cultivation in Egypt is the limited quantity of irrigation water from the Nile River and the scarcity of water.

The Egyptian rice varieties are compatible with Egypt's water, climate, and agricultural conditions. Thus, it is recommended to plant these varieties outside the borders of the Nile Delta region, in the new reclaimed lands under good water management using modern irrigation systems. This requires the cooperation of all the scientific authorities responsible for cultivating this crop to achieve the goal of self-sufficiency and provide a surplus of rice production for export, in addition to achieving a profitable income for the farmers.

Keywords: Rice cultivation in Egypt; Sustainable Rice Cultivation; Water saving; Rice History

1. Introduction

Rice is an essential food for thousands of millions of people and, after wheat, it is the most important crop for human food. It is deeply embedded in the cultural heritage of many societies. It is the staple food for more than half of the world population.

The theme of the International Year of Rice in 2004 was: “Rice is life” (FAO, 2004**).** Rice is life reflects the importance of rice as a primary food source and is drawn from an understanding that rice-based systems are essential for food security, poverty alleviation and improved livelihoods.

In Asia alone, people obtain 60 to 70% of their energy intake from rice and its derivatives; it is the most rapidly growing food source in Africa and is significant to food security in an increasing number of low-income food-deficit countries.

Rice-based production systems and their associated post-harvest operations employ nearly 1 billion people in rural areas of developing countries and about four-fifths of the world's rice is grown by small-scale farmers in low-income countries.

Efficient and productive rice-based systems are therefore essential to economic development and improved quality of life, particularly in rural areas.

Egypt is the largest rice producer in the Middle East region and is the most important rice market in the North Africa. The rice market in Egypt is segmented based on production, consumption, import and export **(**Mordor Intelligence, 2022**).** Rice is grown mostly in the Nile Delta, mainly because of its thick clay texture soils. The climatic characteristics of the country are favourable to a high yield of rice, being one of the most important summer crops of the region **(**Elbasiouny and Elbehiry, 2020).

Rice is considered the most popular and important field crop in Egypt for several reasons: as a staple food for more than 50% of Egyptians, as a land reclamation crop for improving the productivity of the saline soils widely spread in Nile Delta and coastal area, low cultivation costs and higher profitability in comparison to other summer field crops, such as maize and cotton, and for its storability for long periods of time, and finally it is a social crop as it allows every person of the farming families to find work in rice fields and gain money during the growing season.

For these reasons, great efforts have been made by the Egyptian Rice Research and Training Center, together with other Institutes, to develop high-yielding and pest resistant modern Egyptian rice varieties with high grain quality. Almost all these varieties are resistant to blast disease and many of them are tolerant to different abiotic stresses such as drought, salinity, and heat waves, in addition, some of them are early maturing varieties (short growing season) which allows the saving of 30% irrigation water every year.

As a result of these efforts, Egypt has now many highly stable yielding varieties that increased the national average yield to about 9.5 tha^{-1} (Elmoghazy and Elshenawy, 2018**)**, which is considered one of the highest yield averages worldwide and due to this, Egypt ranked 14th on the list of 113 rice producing countries worldwide.

Water shortage is one of the main constraints and major limiting factor facing the economic development plan of Egypt. Geographically Egypt is in a dry climate zone where rainfall is scarce, the desert covers most of its land and its ground water reservoir is deep, not renewable, and overexploited (Mostafa et. al., 2021). The fixed share of Egypt from the Nile (55.5 Bm^3) together with threatening water projects (e.g., the new Ethiopian Renaissance Dam) constituting a serious concern about water availability (Dakkak, 2023).

Due to the high productivity and quality of Egyptian rice worldwide, its high-water needs, and Egypt's water scarcity conditions, Ministry of Water Resources and Irrigation issued the rice cultivation policy document.

The document identified nine governorates to grow rice; the nine governorates are: Kafr El-Sheikh, Sharqia, Damietta, Dakahlia, Beheira, Alexandria, Ismailia, Port Said and Gharbia and it was prohibited in south of Egypt, Suez, South Sinai, Marsa Matrouh, Kalioubiya, Menoufiya and Giza.

The main constraint of rice cultivation in Egypt is the limited quantity of irrigation water from the river Nile, especially in the Northern part of the Nile Delta.

2. Where in the world did rice originate

It is impossible to pin-point exactly when mankind first realized that the rice plant was a food source and began its cultivation. Many historians believe that rice was grown as far back as 5000 years BC.

Archaeologists excavating in India discovered rice which could be dated to 4530 BC. However, the first records that mention rice originate from China in 2800 BC (The Rice Association, 2021).

The Chinese Emperor, Shen Nung**,** realized the importance of rice to his people and to honour the grain he established annual rice ceremonies to be held at sowing time, with the emperor scattering the first seeds. Although we cannot identify China, India or Thailand as being the home of the rice plant (indeed it may have been native to all), it certainly originated in Asia (The Rice Association, 2021).

The current scientific consensus, based on archaeological and linguistic evidence, is that Oryza sativa rice was first domesticated in the Yangtze River basin in China 13,500 to 8,200 years ago (Vaughanet al., 2008; Zhanget al*.,* 2012). Cultivation, migration and trade spread rice around the world—first to much of east Asia, and then further abroad, and eventually to the Americas as part of the ‘Columbian exchange’. The now less common

Oryza glaberrima rice was independently domesticated in Africa around 3,000 years ago **(**Choi, 2019). Other wild rice species have also been cultivated in different geographies, such as in the Americas (Photos 1-3).

3. The origin of rice in Egypt

Some historians mentioned that rice was not known in Ancient Egypt. There are indications that it was probably introduced to Egypt and the surrounding region, through the expeditions of Alexander the Great who imported the grain from India in the 4th Century BC (Sami Aziza, 2016).

Rice was a delicacy, in comparison to other crops such as wheat. The information gathered by historians on the origins, nature and evolution of rice production and consumption in Medieval Egypt is scarce and often incomplete. What is known with certainty, is that rice is one of the many crops introduced to Egypt in the 8th Century, possibly imported from Spain, and that it flourished most notably after the Ottoman conquest of Egypt in 16th Century (Lasheen, 2022).

Egyptian rice which was called ‘Egypt’s most royal commodity’ was a palace favourite, feeding the sultan and a circle of elites (Griffith, 2017). The Ottomans demand for Egyptian rice paved the way for the rise of the rice cultivation in the coastal cities of Dumyat, Rasheed and Faraskour. It could be assumed that rice acquired an esteemed position in Egyptian agriculture, not just because it was profitable but because it was culturally perceived as a royal staple. This is supported by the proliferation of Ottoman rice recipes that carry the same name till today, although slightly altered to suit the Egyptian taste.

Photo 1. China Linares (2002)

Photo 2, Africa Ricepedia.org (2023)

Photo 3. India, lamy (2010)

The heavenly smell of freshly baked Roz Mu'ammar - a rice dish baked in milk and crème – filled the air (Photo 4).

Photo 4. Roz Mu'ammar; A simple sumptuous- Egyptian treat Heritage special (Sami Aziza, 2016)

As rice cultivation spread, rice became a global staple crop important to food security and food cultures around the world. Local varieties of Oryza sativa have resulted in over 40,000 cultivars of various types. More recent changes in agricultural practices and breeding methods as part of the Green Revolution and other transfers of agricultural technologies has led to increased production in recent decades, with emergence of new types such as golden rice, which was genetically engineered to contain beta carotene (Nguyen, 2023).

4. Rice production worldwide

After sugarcane and corn, rice is the third most produced agricultural crop in the world. For over half of the world's population, rice is the primary food staple, with Asia, Sub-Saharan Africa, and South America being the largest consumers of it. Oryza Sativa, the primary species of rice, is believed to have originated in Asia from the Graminaceae family (World Population Review, 2023).

It is assumed that about 515 million tons of rice will have been produced worldwide in 2022. India remains the largest exporter of rice in the world, while the Sub-Saharan African region is the most important importer.

More than 80% of the world's rice is harvested in 10 countries, located in Asia. Together, China and India account for more than half of the rice produced globally. Rice continues to be a major source of calories and nutrition. The top 10 countries who produce the most rice in metric tons in 2022 as represented in Figure 1.

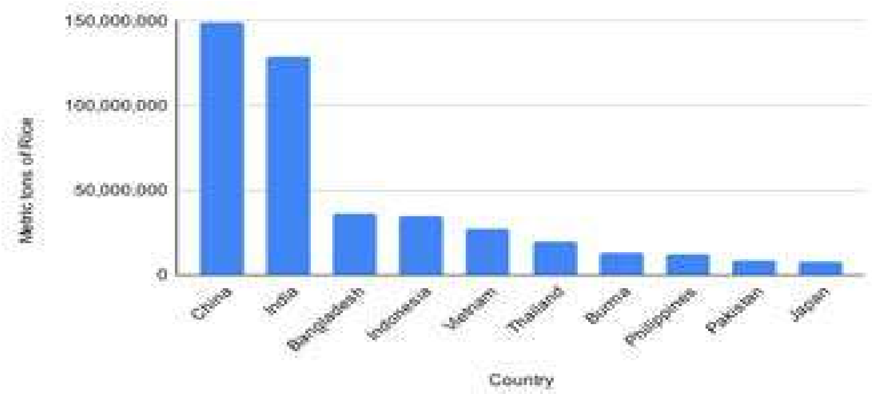


Figure 1 Rice Production by Country in 2022. World Population Review, (2023)

5. Rice production in Egypt

5.1 Rice cultivation area

The rice cultivation area in Egypt is restricted to the north, east, and west parts of Nile Delta because the Ministry of Irrigation guarantees a special irrigation regime for the northern part of the Nile Delta closer to the Mediterranean Sea to mitigate and prevent the intrusion of seawater as about 25 to 30% of the land in the lower Nile Valley is affected by different degrees of salinity. In these areas, rice production helps to leach the salt from upper soil layers and thus reclaim the land for agriculture. In addition, outside the rice belt, it is also cultivated in a limited area in middle of Egypt at Fayoum governorate (Fig. 2). On average, rice occupies about 22% of the cultivated area in Egypt and consumes about 18% of available water from Nile River (Badawi,et.al., 2002).

5.2 Rice Production and Consumption

Rice is one of the major field crops in Egypt. It occupies about 0.65 million ha, i.e., around 20% of the cultivate area in Egypt and its production was 6.0 million tons (Mt) in 2000/2001, contributing about 20% to per capita cereal consumption. In 2010/2011 and in 2018/2019 there was a decline in production and, in general, the values have been decreasing over the past years. This is probably because the government was trying to restrict the rice area to save water, since large amounts of water are necessary to grow rice (Elmoghazy et.al., 2016).

Improving the productivity of rice systems would contribute to hunger eradication, poverty alleviation, national food security and economic development as rice provides 27% of dietary energy supply and 20% of dietary protein intake.

Figure 2 Rice cultivation area in Egypt, Elmoghazy and Elshenawy, (2018)

5. 3 Rice towards growth and development

The growing popularity of agricultural equipment, like power tiller, seeder, weeder, reaper, Artificial Super Intelligence (ASI), thresher, and other post-harvest machinery, has improved the yield by reducing post-harvest, as well as cultivation losses. Moreover, with the increased investment by the Egyptian government in the Research and Development, R&D activities, in collaboration with various stakeholders, the rice market is steered towards growth and development (Mordor Intelligence, 2022).

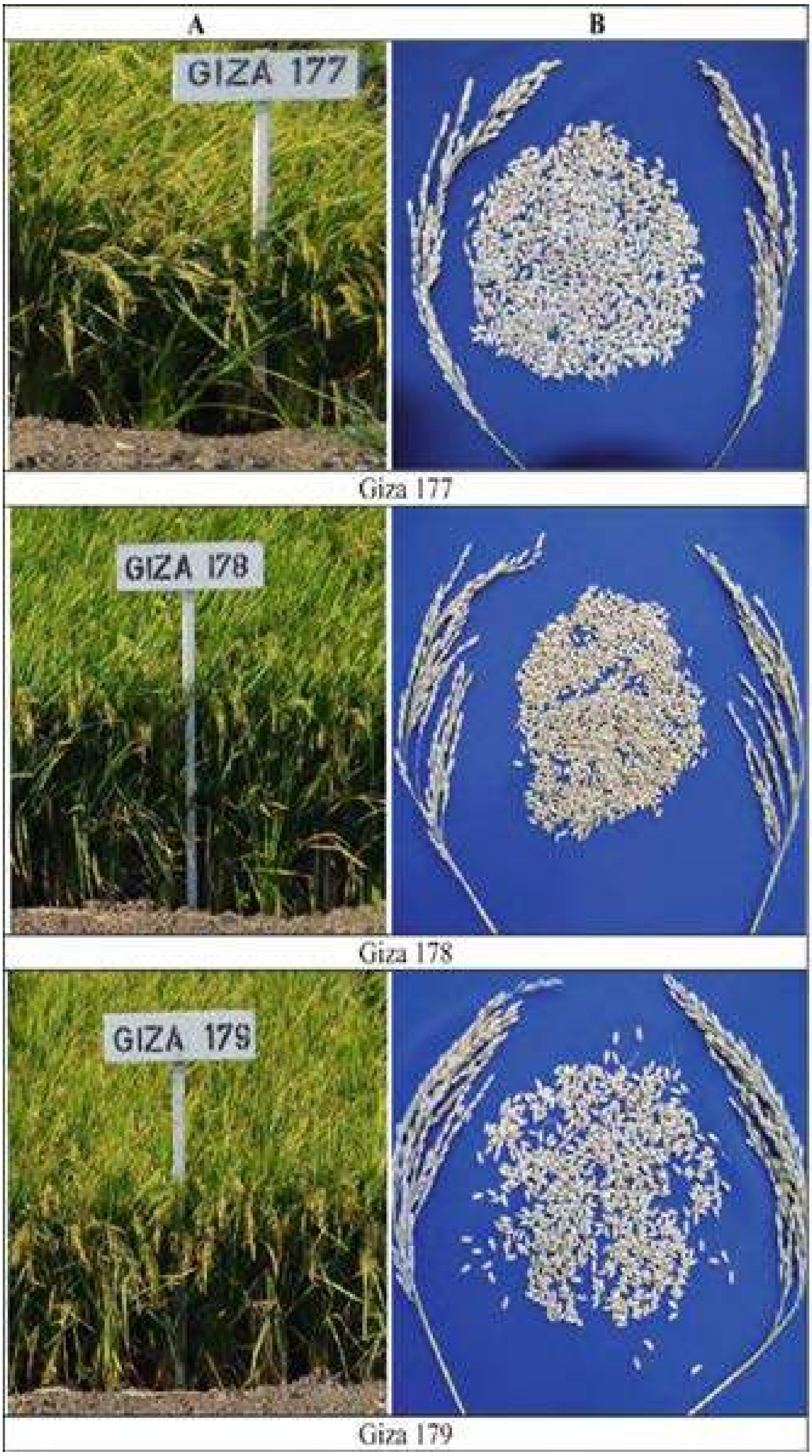
6. Egyptian rice types, varieties, and time of planting and harvesting

The high solar radiation, the long days and the cool nights between May and September are favourable to a high rice yield. So, the Egyptian Rice is sown from the beginning of May till the end of June and its harvest season starts in the middle of August till the middle of October of the year.

The Egyptian Rice type is considered to have short and medium round grains. Most of the planted rice varieties are japonica and the most famous varieties are Sakha 101, 102, 104 and Giza 177, 178.

These promising varieties are characterized with high yield potential, high grain quality, and high blast resistance and many of them are tolerant to different abiotic stresses such as drought, salinity, and high temperature. Some of them are early maturing varieties (short growing season) that allow saving of about 30% irrigation water consumption every year (Aidy. and Maximos, 2006).

The national average yield per unit area was 9.3 tons ha−1 at the end of the period (1987–2000) which represents a 66% increase from the 5.6 tons ha^{-1} for the 1975–1986 period and a 27% increase from the 7.3 tons ha^{-1} for the1987–1997 period (Negm and Abu-hashim, 2019).


A
B
GIZA 177
Giza 177
GIZA 178
Giza 178
GIZA 179
Giza 179

Some of the modern and commercial Egyptian rice varieties are presented in Photos, 5A, 5B and 5C.

Photo 5 A. Egyptian Rice Varieties, Giza 177, Giza 178, Giza 179. Elmoghazy and Elshenawy (2018) Side (A) shows the plant panicles, while Side (B) shows the grain shape.

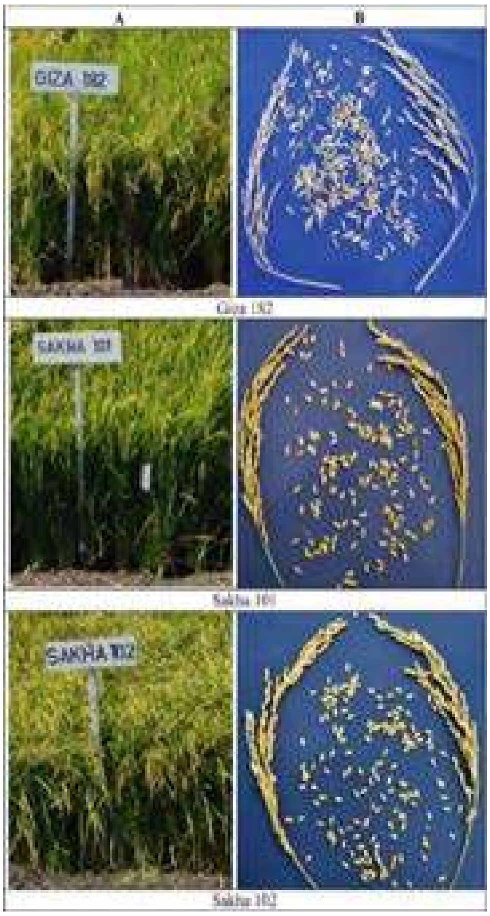


Photo 5B, Photo 5B, Egyptian Rice Varieties, Giza 182, Sakha 101, Sakha 102. Elmoghazy and Elshenawy, (2018)

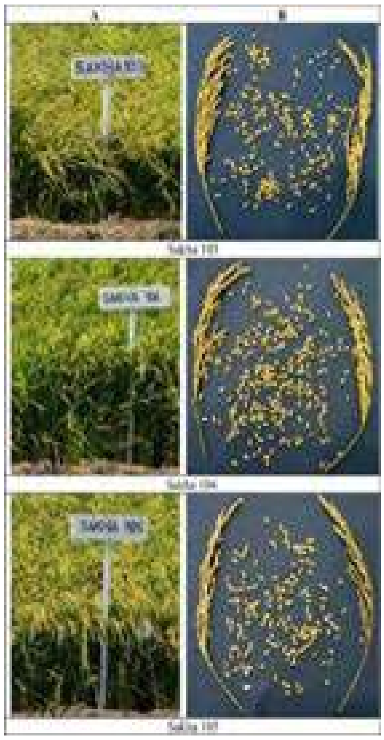


Photo 5C. Egyptian Rice varieties, Sakha 103, Sakha 104, Sakha 105. Elmoghazy and Elshenawy, (2018)

7. The role of Rice Research and Training Centre in promoting the rice cultivation in Egypt

The Rice Research and Training Center (RRTC) (Photo 6) was established in 1987 at Sakha, Kafr Elsheikh in cooperation with the United States Agency for International Development (USAID) and the International Rice Research Institute (IRRI), to be specialized in rice research, seed production, training, and extension. Since this date, great enhancements in rice production in Egypt were achieved (Negm and Abu-hashim, 2019).

Rice Research & Training Center belongs to the Field Crops Research Institute, Agricultural Research Center, its research activities include the following:

1. Breeding & variety production (Classic breeding, Biotechnology, Hybrid Rice).
2. 2-Agronomy (Agriculture Practices, Fertilizers, Irrigation and Plant physiology)
3. 3-Seed varieties genes protection
4. 4-Technology transfer

Photo 6. Rice Research and Training center in EGYPT, Elmoghazy and Elshenawy (2018)

8. Rice import and export status in Egypt

Most of the rice in Egypt is grown under irrigated conditions in which the fields are flooded from planting to harvest **(**Photo 7). Rice is said to use about 10 billion cubic meters, which constitutes 20% of Egypt's water resources.

Rice consumes about two and a half times the amount of water needed to grow wheat or maize, according to the International Rice Research Institute (IRRI) (Elmoghazyand Elshenawy, 2018).

Photo 7. Flood Rice Cultivation. Egypt Today staff (2019)

The availability of freshwater resources in Egypt is limited to the River Nile, groundwater from both renewable and non-renewable aquifers, limited rainfall along the Northern Coast, and flash floods in Sinai. Groundwater also exists in the non-renewable deep aquifers of the western desert and Sinai. Thus, Egypt currently receives approximately 98% of its freshwater from the river Nile outside its international borders. This situation is considered a significant challenge for the Egyptian water policy and decision makers. Rainfall is very scarce and occurs during the winter season (Mostafa et.al.,2021). The fixed Nile water quota together with threatening water projects (e.g., the new Ethiopian Renaissance Dam) constitute a concern (Dakkak, 2023). Egypt's per capita share of water has decreased to 550 cubic meters per year, which is almost half of the water poverty level (1,000 cubic meter per year). Despite the high productivity and quality of Egyptian rice worldwide, its high water needs, and Egypt's water conditions, led the Ministry of Water Resources and Irrigation to issue rice cultivation policy document. In February 2018, Ministry of Irrigation and Water Resources decided to reduce the rice agriculture area in Egypt from 1,700,000 feddans to 724,200 feddans (1 feddan =0.42 ha) to rationalize water in Egypt.

The decision identified nine governorates that could grow rice; the nine governorates are: Kafr El-Sheikh, Sharqia, Damietta, Dakahlia, Beheira, Alexandria, Ismailia, Port Said and Gharbia and rice cultivation was prohibited in South Egypt, Suez, South Sinai, Marsa Matrouh, Qalioubiya, Menoufiya and Giza (the lower valley) as shown in (Fig. 3).

Figure 4 shows the old, cultivated rice area, where rice was cultivated all over the Nile valley area. At that time, 2018, experts expected that reducing the rice cultivated areas would lead to a decrease in production, such a decrease would lead to higher prices and a trend towards higher imports to cover the needs of the local market to ensure food security.

In 2019, Egypt produced about 3.3 million tons, while the Egyptians' annual consumption of rice was estimated at 4.3 million tons; therefore, domestic production remained insufficient. For this deficit in production to be compensated, Egypt had to turn from an exporting country (Figure 6) to be an importing country due to the water shortage crisis the country is suffering from.

Figure 3 Recent Rice Cultivated Area
USDA (2022)

Figure 4 Old Rice Cultivated Area
USDA (2019)

In the same year, in March 2019, the Ministry of Water Resources, and Irrigation (MWRI) and the Ministry of Agriculture and Land Reclamation (MALR) increased the allotted rice cultivated area for the year 2019 to 1,074,200 feddans (~451,920 ha) up from the 724,200 feddans (~304,080 ha) authorized in 2018. This included 304,164 ha planted with current early maturing varieties (short growing season). In addition to 84,000 ha planted with drought tolerant varieties and 63,000 ha planted with varieties tolerant to soil salinity conditions. Both drought and salt tolerant varieties have been distributed across the nine governorates.

Figure 5 shows that generally, rice exports have been decreasing over the years and rice imports have been increasing due to the higher demand compared to production (Mordor Intelligence, 2022). Export was taking place between 2000 and 2011/2012. After that, the import of rice was higher than the export and diminished from 2017 onwards.

Over the years 2020 and 2022, the Ministry of Water Resources and Irrigation (MWRI) re-published the Ministerial Decree of the year 2020 indicating the Delta provinces that would be planting rice in the year 2021. The allotted rice cultivated area for the year 2021 was set for 1,074,200 feddans (~451,164 ha) in nine governorates (Wally and Akingbe , 2021).

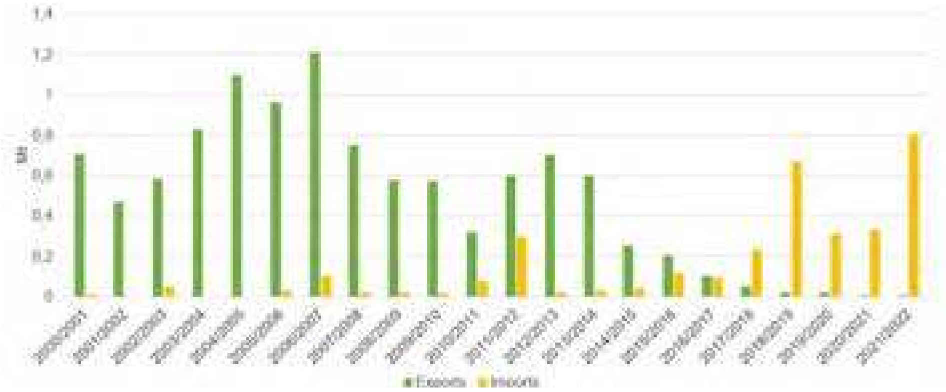


Figure 5. Exports and Imports (trade year) of rough rice between the years 2000 and 2022 (Sousa, et al., 2023)

9. Ways to overcome water scarcity in rice production.

9.1 The Ministry of Agriculture has identified 53 varieties of strategic water-saving, focusing on breeding, which included seven varieties of rice.

These varieties give high productivity, resistance to disease, and adapted to various water and climatic conditions, as well as having a short growing season, to achieve high efficiency in the use of irrigation water, which saves water quantities that can be used for cultivation of other crops.

9.2 The farmers' syndicate suggested using modern irrigation methods like drip and sprinkler irrigation, and cultivating non-irrigated rice strains such as Sakha 101, 102, 104 and Giza 177, 178 varieties.

9.3 Abdelhalim et al. (2017) mentioned that, in case of water scarcity, application of irrigation every 12 days with 3 cm depth can be recommended because it resulted in similar water productivity value as application of irrigation every 6 days with 7 cm depth for both cultivars Giza178 and Oraby2. Giza178 can use water more efficiently and attains higher water productivity, compared to Oraby2. Therefore, it can be recommended to be used under water scarcity conditions in Egypt.

10. Awards for Egyptian researchers towards irrigation water saving and development of rice crop

10.1. ICID (International Commission on Irrigation and Drainage) awards

Yousri Ibrahim Atta of the Water Management Research Institute, National Water Research Centre received the 2008 Innovative Water Management Award for his paper "Innovative Method for Rice Irrigation with High Potential of Water Saving". Hagarey of the Desert Research Centre, Irrigation and Drainage

Unit, Soil Conservation and Water Resources Department won the "2016 ICID WatSave Young Professionals Award" for his work to "Save Irrigation Water using an Innovative Machine for Soil and Water Management for Rice Crop Cultivation (SWMR)".

10.2 Egyptian award (2022)

The Egyptian Ministry of Agriculture honored Dr Hamdi al-Mawafi, head of the National Rice Development Project, after he received the gold medal at the 2022 Geneva International Exhibition of Inventions, for an applied innovation by devising the giant Sakha Super 300 rice variety. The new type of rice is characterized by the quality of grains and the ability to withstand difficult conditions such as water scarcity, salinity, and heat.

11. Conclusion

The theme of the International Year of Rice 2004 (FAO, 2004) was Rice is life. Rice is life reflects the importance of rice as a primary food source and is drawn from an understanding that rice-based systems are essential for food security, poverty alleviation and improved livelihoods.

In Egypt, rice is rated among the main important field crops after wheat and maize. This importance comes, for its low cultivation costs, higher profitability, its storability for long periods of time. Rice cultivation also helps limit seawater intrusion into the northern Nile Delta lands. Rice could be used also as a land reclamation crop to Nile Delta lands to improve the productivity of saline soil. Moreover, rice is an important export crop and could be an important source of foreign currency. Finally, rice is a job creator as it needs many workers during its growing season.

Egypt produced many varieties of rice, which are characterized by their resistance to drought, salinity, and high temperatures/heatwaves, in addition to, the short-duration varieties that save a large proportion of irrigation water. These varieties were produced by the efforts of the Egyptian Rice Research and Training Centre (RRTC) with some other research institutes. The productivity of these varieties is up to 9.3 tons ha^{-1} which is considered one of the highest averages worldwide.

The main constraint of rice cultivation in Egypt is the limited quantity of irrigation water from the River Nile and the scarcity of water, especially in the North part of the Nile Delta.

12. Recommendation

Egyptian rice varieties are characterized by their resistance to drought, salinity, and resistance to high temperatures and heatwaves. These, characteristics are compatible with Egypt's water and climatic conditions.

Therefore, it is recommended to expand the rice cultivated area by planting these varieties outside the borders of the Nile Delta region, in the newly reclaimed lands under the modern irrigation systems such as drip irrigation to achieve self-sufficiency and provide a surplus for export and generate good income for the farmers.

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SALTMED MODEL AS A TOOL FOR MANAGEMENT OF WATER, CROPS, FIELD, AND N –FERTILIZERS

Prof. Dr. Ragab Ragab[1]

ABSTRACT

Models can be very useful tools in agriculture water management. They could help in irrigation scheduling and crop water requirement estimation and to predict yields and soil salinization. SALTMED model is a generic model that can be used for a variety of irrigation systems, soil types, crops and trees, water application strategies and different water qualities. The current version was successfully tested against field experimental data (Ragab et al., 2005a&b, Ragab et al., 2015, Ragab 2020).The current version, SALTMED includes sub-models for crop growth according to heat units/degree days, crop rotations, nitrogen dynamics, soil temperature, dry matter and yield, subsurface irrigation, deficit irrigation including the Partial Root Drying, PRD, drainage flow to tile or open drains systems, presence of shallow groundwater, evapotranspiration using Penman-Monteith equation, with different options to obtain the canopy conductance. The current version allows up to twenty fields or treatments to run simultaneously.

The model was applied on field experiments in different countries. These experiments included several crops, different water qualities, such as saline water, treated wastewater and fresh water, different irrigation strategies such as deficit irrigation (applying less water than the total crop water requirement) and applied water stress during certain growth stages.

The model has been validated with field data of : drip irrigated tomato and potato crops in Syria, Egypt, Crete, Serbia and Italy (Ragab et al., 2005b and 2015, Afzal et al., 2016), sugar cane using sprinkler irrigation in Iran (Golabi et al., 2009), cotton using drip irrigation in Greece (Kalfountzos et al., 2009), quinoa using saline water in Denmark (Razzaghi et al., 2011), quinoa, sweetcorn and chickpea using drip irrigation in Morocco (Hirich et al., 2012), vegetable crops in Brazil (Montenegro et al., 2010), quinoa using saline water in Italy (Pulvento et al., 2013), amaranth using saline water in Italy (Pulvento et al., 2015b), rainfed and irrigated chickpea in Portugal (Silva et al., 2013), quinoa under deficit drip irrigation in Morocco (Fghire et al., 2015), sweet pepper in green houses using saline water in Turkey (Rameshwaran et al., 2015, 2016b), legumes (lentil, chickpea and faba bean) using saline water in Syria (Arslan et al., 2016, Rameshwaran et al., 2016a), quinoa using fresh and saline water in Turkey (Kaya and Yazar, 2016) and potato using gated pipes in Egypt (El-Shafie et al., 2017). In all these studies the model proved its reliability and ability to predict the field measured yield, dry matter, soil moisture and salinity. The model was also used to derive the salinity-yield response function (Arslan, 2016; Rameshwaran et al., 2015, 2016a, 2016b) and to predict the impact of climate change on the amaranth and corn water requirement, yield, sowing and harvest dates and the length of the growing season in two countries, Italy and Morocco (Pulvento et al., 2015a; Hirich et al., 2016). The model has been intensively used in Egypt on a variety of field crops (Abdelraouf and Ragab 2017, 2018a,b,c, Abdelraouf et al., 2020, Dewedar et al., 2021, Marwa et al., 2020, El-Shafie et al., 2017), in Pakistan (Chauhdary et al., 2019, 2020), in Iran (Basiri et al. 2020, Dastranj et al., 2018), in Portugal (Siva et al., 2013, 2017) and in Morocco (Hirich et al., 2012, 2016 and 2020, Filali et al., 2017, Fghire et al., 2015, 2017). More information and applications are published in a special Issue of Journal of Irrigation and Drainage (Ragab 2020).

Keywords: SALTMED model, Salinity, Soil moisture, Crop growth, Dry Matter, Yield, Agricultural Water Management, Nitrogen Fertilizer Management, Irrigation, Drainage, Deficit Irrigation, Partial Root Drying, PRD, Crop rotation, Evapotranspiration, plant water uptake, Nitrogen Dynamics

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1. Introduction

Globally, agriculture on average is using 70% of the freshwater resources. Rainfed agriculture represents almost 75% of total agriculture area and produces 60% of the global food production, while irrigated agriculture represents nearly 25% of the total agricultural area but produces 40% of the global food production. This fact shows the positive impact of irrigation. Farmers in areas dominated by rainfed agriculture started to apply supplemental irrigation after seeing the benefit of additional irrigation supplement to maximize the yield. Given such a huge amount of water is needed for food production, some regions are struggling to produce enough food and feed for the growing populations. In addition, the changing climate especially in semi-arid areas resulted in water shortage caused by frequent years of below-average rainfall and severe drought. Even in humid regions, drought events became very frequent and the rainfed agriculture is frequently supported by supplemental irrigation during the water shortage periods. Deficit irrigation is now in practice and drought tolerant varieties are sown to cope with the water scarcity. A truly integrated approach is essential to encourage the increased use of poor quality water for irrigation, in order to both minimise drainage disposal problems and maximise the beneficial use of multiple water sources.

At present, there is a competition among several sectors for fresh water. As a result, the agriculture sector in different parts of the world searched for alternative water resources sometimes known as non-conventional water resources e.g., re-use of agriculture drainage water, use of brackish water (groundwater), use of seawater, desalinated saline water or treated wastewater. In applying these non-conventional methods, a great deal of care should be exercised in order not to harm the environment or cause soil degradation (Ragab, 1997, 1998, 2002, 2004; Hamdy et al., 2003; Malash et al., 2008; Choukr-Allah, 2010, 2012). In addition, the concept of deficit irrigation (applying less water than the crop water requirement) by subjecting the plant to mild stress in the growth stages less sensitive to water stress is being adopted in different parts of the world.

The impact of using poor quality water on soil and the environment is a slow long-term process and therefore short-term experiments are unable to show the impact. For that reason, models to predict the long term effect on soil and environment, crop yield, soil water and salinity under different strategies of water management (deficit irrigation and alternative use of fresh and poor quality waters) and leaching requirements have been developed in parallel with the field and greenhouse experiments. Models can be very useful tools in agriculture water management. Not only could they help in irrigation scheduling and estimating crop water requirements calculation, but they could also be used to predict dry matter and yields, soil moisture, soil moisture deficit, soil salinity and soil nutrient status. SALTMED model has been developed for generic applications. It accounts for different irrigation systems (Basin, Furrow, Sprinkler, Centre Pivot, Drip and rainfed), irrigation strategies (deficit irrigation, Partial Root Drying, PRD), presence of drainage systems and shallow groundwater, different crops and soil types and N-fertilizer applications.

The SALTMED model (Ragab, 2002, 2005, 2015, 2020) has been developed to predict dry matter and yield, soil salinity and soil moisture profiles, salinity leaching requirements and soil nitrogen dynamics and nitrate leaching, soil temperature, plant water uptake and evapotranspiration. The model is user friendly and easy to use benefiting from the Windows™ environment; however, it is a physically based model using the well-known water and solute transport, evapotranspiration, and water uptake equations. The SALTMED model can be freely downloaded from the links provided at the end of this chapter.

2. Brief description of the main processes in the SALTMED model

In early 2000, the EU funded SALTMED project to study the long-term impact of using saline water in the Mediterranean region. This project has led to the development of the SALTMED model (downloadable from the International Commission on Irrigation and Drainage, ICID web site: http://icid-ciid.org/inner_page/41). The model has been developed further through three more EU funded projects EU, SWUP-MED, SAFIR and Water4Crops. The results were reported in several publications and special issues. “SALTMED Publications in Irrigation and Drainage, Virtual Issues first published: 20 May 2020 Last updated: 20 May 2020. Wiley on line Library” https://onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)1531-0361.saltmed-publications.”

The SALTMED model includes the following key processes: evapotranspiration, plant water uptake, water and solute transport under different irrigation systems, nitrogen dynamics and dry matter and biomass production. A brief description of the above-mentioned processes will be given in the following sections.

2.1. Evapotranspiration

Evapotranspiration has been calculated using the Penman-Monteith equation according to the modified version of Allen et al. (1998) in the following form:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1a)$$

where ET_o is the reference evapotranspiration, (mm day^{-1}), R_n is the net radiation,

(MJ m^{-2} day^{-1}), G is the soil heat flux density, (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height, (°C), Δ is the slope of the saturated vapour pressure curve,

(kPa °C^{-1}), γ is the psychrometric constant, 66 Pa °C^{-1}, e_s is the saturated vapour pressure at air temperature (kPa), e_a is the prevailing vapour pressure (kPa), and U_2 is the wind speed at 2 m height (m s^{-1}). The calculated ET_o here is for short well-watered green grass. In this formula, a hypothetical reference crop with an assumed height of 0.12 m, a fixed surface resistance of

70 s m^{-1} and an albedo of 0.23 were considered.

In presence of stomata/canopy surface resistance data, one could use the widely used equation of Penman-Monteith (Monteith, 1965) in the following form:

$$\lambda E_p = \frac{\Delta R_n + \rho C_p \frac{(e_s - e)}{r_a}}{\Delta + \gamma \frac{(1 + r_s)}{r_a}} \quad (1b)$$

where "r_s" and "r_a" are the bulk surface and aerodynamic resistances (s m^{-1}).

The r_s can be measured or calculated from environmental and meteorological parameter or from the leaf water potential and Absecic Acid, ABA.

In the absence of meteorological data (temperature, radiation, wind speed etc.) and if Class A pan evaporation data are available, the SALTMED model can use these data to calculate ET_o according to the FAO procedure (Allen et al., 1998). The model can also calculate the net radiation from solar radiation according to the FAO procedure if net radiation data are not available. The crop evapotranspiration ET_c is calculated as:

$$ET_c = ET_o(K_{cb} + K_e) \quad (2)$$

where K_{cb} is the crop transpiration coefficient (known also as basal crop coefficient) and K_e is the soil evaporation coefficient. The values of K_{cb} and K_c (the crop coefficients) for each growth stage and the duration of each growth stage for different crops are available in the model's database. These data can be used in the absence of measured values. K_e is calculated according to FAO (Allen et al., 1998). K_{cb} and K_c are adjusted according to FAO (Allen et al., 1998) for wind speed and relative humidity if different from 2 m s^{-1} and 45%, respectively. The SALTMED model runs with a daily time step and uses K_{cb} and K_e. These parameter values are not universal, and their values differ according to climatic conditions and other factors.

2.2. Plant water uptake in the presence of saline water

The Actual Water Uptake Rate

The formula adopted in the SALTMED model is that suggested by Cardon and Letey (1992), which determines the water uptake S (d^{-1}) as:

$$S(z,t)=\left[\frac{S_{\max}(t)}{1+\left(\frac{a(t)h+\pi}{\pi_{50}(t)}\right)^{3}}\right]\lambda(z,t) \quad (3)$$

where S_{max}(t) is the maximum potential root water uptake at the time *t*; *z* is the vertical depth taken positive downwards, $\lambda(z,t)$ is the depth-and time-dependent fraction of total root mass, L is the maximum rooting depth, *h* is the matric pressure head, π is the osmotic pressure head; π_{50} (t) is the time-dependent value of the osmotic pressure at which S_{max}(t) is reduced by 50%, and *a*(t) is a weighing coefficient that accounts for the differential response of a crop to matric and solute pressure. The coefficient *a*(t) equals $\pi_{50}(t)/h_{50}(t)$ where h_{50}(t) is the matric pressure at which S_{max}(t) is reduced by 50%.

The maximum water uptake S_{max} (t) is calculated as:

$S_{max}(t) = ET_o(t) * K_{cb}(t)$ (4)

The values of h_{50} and π_{50} can be obtained from experiments or from literature (Rhoades et al., 1992).

2.3. The relative crop yield, RY

Due to the unique and strong relationship between water uptake and biomass production, and hence the final yield, the relative crop yield RY is estimated as the sum of the actual water uptake over the season divided by the sum of the potential water uptake (under no water and salinity stress conditions) as:

$$RY=\frac{\sum S(x,z,t)}{\sum S_{\max}(x,z,t)} \quad (5)$$

where x, z are the horizontal and vertical coordinates of each grid cell that contain roots, respectively. actual yield, AY

The actual yield, *AY* is simply obtainable by:

$$AY = RY * Y_{\max} \quad (6)$$

where Y_{max} is the maximum yield obtainable in a given region under optimum and stress-free conditions. This option assumes that salinity and water are the only stressors and all other factors are at optimum level. It is also used for quick answers when one needs to run several "what if" scenarios. The other option to obtain the actual yield is by calculating the daily biomass production and obtaining the actual yield from the harvest index times the total dry matter as given hereunder.

2.4. Crop growth, biomass production and yield

The crop growth, biomass, dry matter production and yield have been calculated based on radiation, photosynthetic efficiency, water uptake, air temperature, leaf nitrogen content, leaf area index, respiration losses and the harvest index. The approach used is very much based on the work of Eckersten and Jansson (1991).

The assimilation rate "A" per unit of area

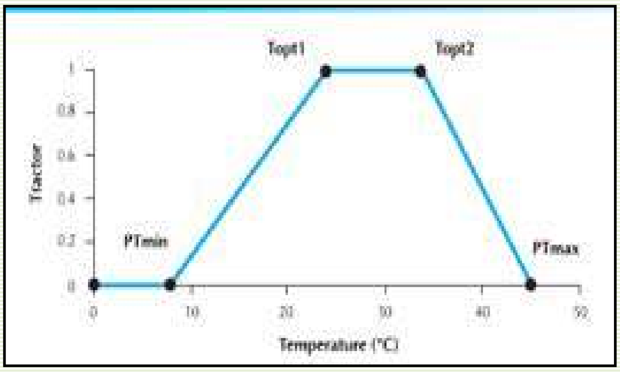
= E*I*f(Temp)*f T)*f (Leaf-N) (7)

Where E is the photosynthetic efficiency (g dry matter MJ^{-1}), I is the radiation input: = Rs $(1- e^{-k*LAI})$, Rs is global radiation (MJ m^{-2} day^{-1}), k is extinction coefficient and LAI is the leaf area index (m^2 m^{-2}). Rs is given in climate data, LAI is interpolated in SALTMED model, assimilation rate" A" per unit of area (g m^{-2} day^{-1}) = E* I* (stress factors related to temperature, transpiration, and leaf nitrogen content). The transpiration stress factor is taken as a ratio of actual plant water uptake to the potential water uptake. The temperature stress is taken as deviation of the average temperature of a given day from the optimum temperature for the growth. The leaf nitrogen stress is taken as the deviation of the leaf nitrogen content of a given day from the optimum leaf nitrogen content.

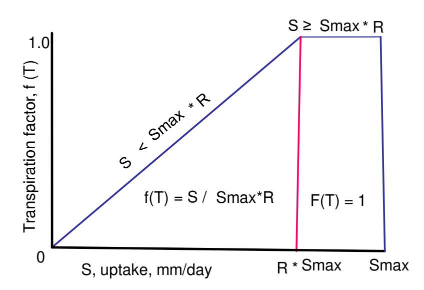
2.4.1. Fixed and variable growth stage periods

There are two options for crop growth. The first option is for the crop to grow according to fixed sowing and harvest dates and each growth stage (initial, development, late) has a prefixed duration in days. The second option is to allow the crop to grow according to the accumulated heat units/degree days (sum of the daily difference between average air temperatures minus minimum temperature required for growth). Each growth stage is completed when a certain number of degree days has been reached. The sowing date and harvest date could, in this case, vary. This is important when studying the impact of climate change on sowing and harvest date as well as the length of the growing season.

Box 2 & 3



Growth-Temperature function



Transpiration –Water stress function

2.4.2. Crop rotation

The model can run with different rotations on different fields (up to 20 rotations). Each rotation could include a variety of different crops, including fallow.

2.5. Water and solute flow

The water flow in soils was described mathematically by the well-known Richard's equation.

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z}\left[K(\theta)\frac{\partial(\psi + z)}{\partial z}\right] - S_w \quad (8)$$

where θ is volume wetness; *t* is the time; *z* is the depth; *K (θ)* is the hydraulic conductivity (a function of wetness); ψ is the matrix suction head; and S_w is the sink term representing extraction by plant roots. The movement of solute in the soil system, its rate and direction, depends greatly on the path of water movement, but it is also determined by diffusion and hydrodynamic dispersion. If the latter effects are negligible, solute flows by convection (Hillel, 1977). The one-dimensional transient movement of a non-interacting solute in soil can be expressed as:

$$\frac{\partial(\theta c)}{\partial t} = \frac{\partial}{\partial z}\left(D_a \frac{\partial c}{\partial z}\right) - \frac{\partial(qc)}{\partial z} - S_s \quad (9)$$

in which *c* is the concentration of the solute in the soil solution, *q* is the convective flux of the *solution*, D_a is a combined diffusion and dispersion coefficient, and S_s is a sink term for the solute representing root adsorption/uptake.

Under irrigation from a trickle line source, the water and solute transport can be viewed as two-dimensional flow (Figure 1) and can be simulated by one of the following:

1. a “plane flow” model involving the Cartesian co-ordinates x and z. Plane flow takes place if one considers a set of trickle sources at equal distance and close enough to each other so that their wetting fronts overlap after a short time from the start of the irrigation.

2. a “cylindrical flow” model described by the cylindrical co-ordinates r and z.

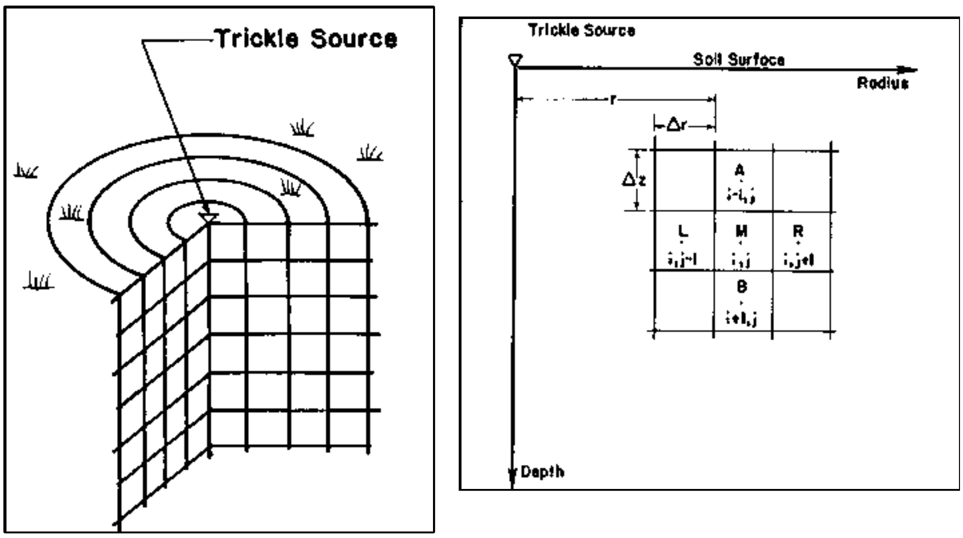


Figure 1. Example of the flow domain under drip irrigation, two-dimensional flow

Cylindrical flow takes place if one considers the case of a single trickle nozzle, or several nozzles spaced far enough apart so that overlap of the wetting fronts of the adjacent sources does not take place. For a stable, isotropic, and homogeneous porous medium, the two-dimensional flow of water in the soil can be described according to Bresler (1975) as:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}\left[K(\theta)\frac{\partial\psi}{\partial x}\right]+\frac{\partial}{\partial z}\left[K(\theta)\frac{\partial(\psi+z)}{\partial z}\right] \quad (10)$$

where *x* is the horizontal co-ordinate; *z* is the vertical-coordinate (considered to be positive downward); K (θ) is the hydraulic conductivity of the soil. The two-dimension solute flow equation becomes:

$$\frac{\partial(C\theta)}{\partial t}=\frac{\partial}{\partial x}\left(D_{xx}\frac{\partial C}{\partial x}+D_{xz}\frac{\partial C}{\partial z}-q_xC\right)+\frac{\partial}{\partial z}\left(D_{zz}\frac{\partial C}{\partial z}+D_{zx}\frac{\partial C}{\partial x}-q_zC\right) \quad (11)$$

In the model, sprinkler, flood and basin irrigation are described by one-dimensional flow equations (e.g., Eqs 8 & 9). Furrow and trickle line source are described by 2-dimensional equations (e.g., Eqs 10 & 11). Trickle point source is described by cylindrical flow equations obtained by replacing x by the radius "r" and rearranging Equations 10 and 11 as given by Bresler (1975) and Fletcher Armstrong and Wilson (1983). The water and solute flow equations were solved numerically using a finite difference explicit scheme (Ragab et al., 1984).

Soil hydraulic parameters

Solving the water and solute transport equations requires two soil water relations, namely the soil water content - water potential relation and the soil water potential - hydraulic conductivity relation. They were taken according to van Genuchten (1980) as:

$\theta(h) = \theta_r + [(\theta_s - \theta_r) / (1+|\alpha h|^n)^m]$ (12)

$K(h) = K_s K_r(h) = K_s Se^{1/2} [1- (1- Se^{1/m})^m]^2$ (13)

Where θ_r and θ_s denote the residual and the saturated moisture contents, respectively; K_s and K_r are saturated and relative hydraulic conductivity respectively, α and n are shape parameters, m = 1 - 1/n and S_e is effective saturation or normalized volumetric soil water content. α, n and λ are empirical parameters.

2.6 Drainage

SALTMED has three options, free drainage at the bottom of the root zone (recharge) or subsurface drainage system open or tile system and shallow groundwater with no drainage system. The drainage flow is based on Hooghoudt's drainage equation (Hooghoudt, 1940) which gives a mathematical relation of the parameters involved in the subsurface drainage of flat land by a system of horizontal and parallel ditches or pipe drains without entrance resistance, placed at equal depth and subject to a steady recharge evenly distributed over the area. The most widely known form of Hooghoudt's equation was presented by Wesseling (1973). In a slightly modified form, it reads:

qL = (8Hm / L) (Kb x De + Ka x Ha) (14)

where q is the steady recharge of water percolating to the water table equal to the drain discharge (m/day or m/hr), L is the drain spacing (m), Hm is the height of the water table midway between drains, taken with respect to the centre of the drain (m), Kb is the hydraulic conductivity of the soil below drain level (m/day or m/h), Ka is the hydraulic conductivity of the soil above drain level (m/day or m/h), De is Hooghoudt's equivalent depth to the impermeable layer below drain level, and Ha=Hm/2 is the average height of the water table above drain level. The equivalent depth De depends on the depth D of the impermeable layer below the drains (Figure 2) as follows:

If D<R: De = D (15)

If R<D<L/4: De = D x L/{(L-D2)+8D x L x ln(D/R)} (16)

If D>L/4: De = L/8ln(L/R) (17)

where R is the drain radius (m). For L/8<D<L/2, Equations 16 and 17 give almost the same result. Equation 16 is the outcome of an analysis of Hooghoudt's theory as reported by Wesseling (1973). Equations 15 and 17 were given by Hooghoudt (1940).

If the drains are open ditches instead of buried pipes, the above equations are applicable with an equivalent radius calculated as R=W/π, where W is the wetted perimeter of the ditch. Further, if the coefficient 8 is changed to 6.4, the equations can be used for drainage with a falling water table (Oosterbaan, 1993).

If drains are open ditches, the diameter needs to be calculated by the user as D=2W/π where W is the wetted perimeter of the ditch. W=B+2h for rectangular, $W = b + 2h\sqrt{1+z^2}$ for trapezoidal and $W = 2h\sqrt{1+z^2}$ for V shaped ditches. B is bottom breadth, h is height of water and Z is the horizontal distance at which the water height drops by a single unit (side slope), Z= 0.25 for rock, 0.5 for hard compact pan, 1.25 for gravel, 1.5 for loam, 2 for loose sandy loam, 2.5 for wet sand, and 3 for light sand and wet clay. http://www.ca.uky.edu/wkrec/openchannelflow.pdf

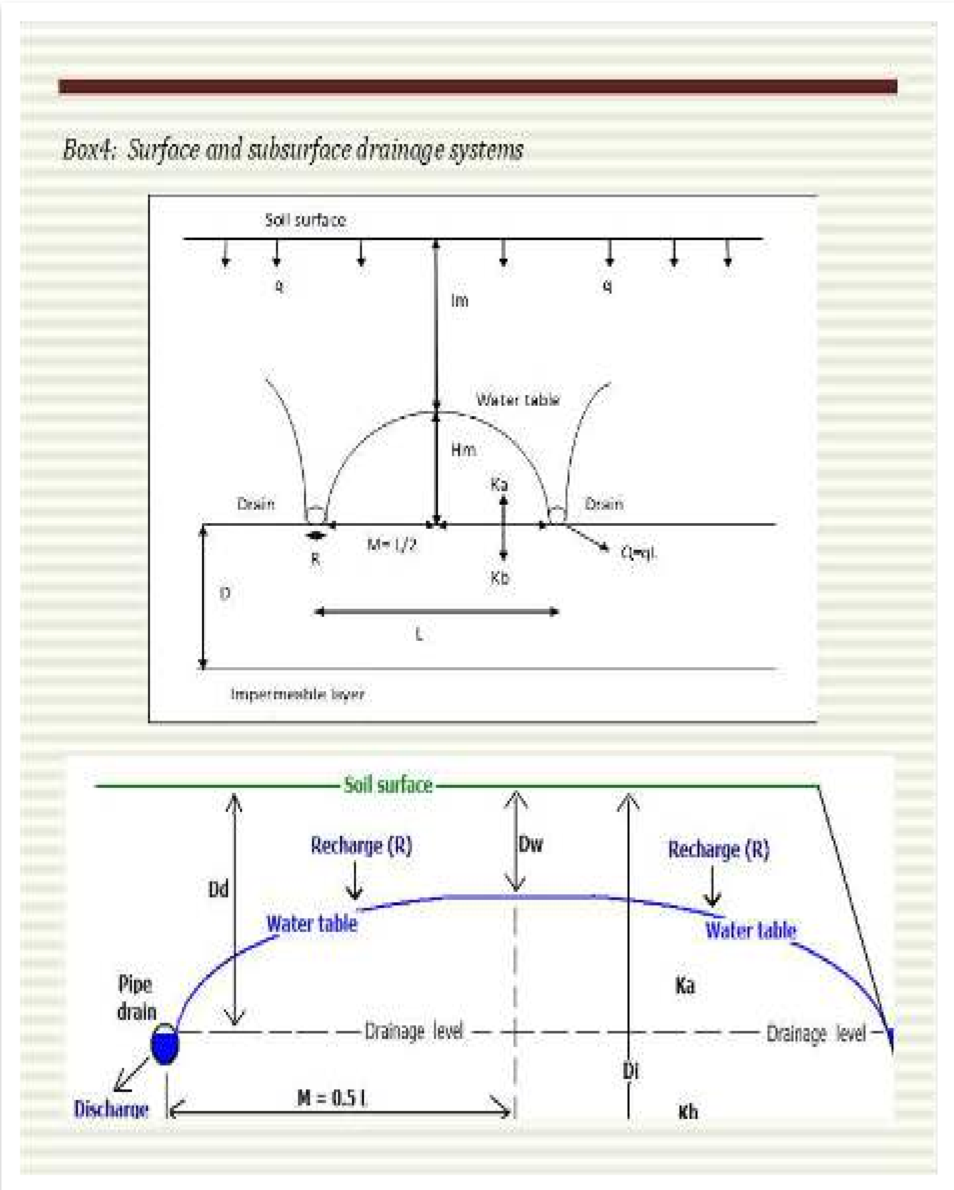


Figure 2: Geometry of open and pipes drainage system

Box 5. Design Parameters for the Drainage System

Table 1: Channel condition & values of the roughness coefficient n.

Channel Condition	Value of n
Exceptional smooth, straight surfaces; enamelled or glazed coating: glass; Lucite; brass	0.009
Good wood, metal, or concrete surfaces with some curvature, very small projection, slight moss or algae growth or gravel deposition; shot concrete surfaced with trowelled mortar	0.014
Rough brick; medium quantity cut stone surface; wood with algae or moss growth; rough concrete, riveted steel	0.015
Well – built earth channels covered with thick, uniform silt deposit; metal flumes with excessive curvature, large projections, accumulated debris	0.018
Smooth well-packed earth; rough stone walls; channels excavated in solid, soft rock, little curving channels in solid loess, gravel or clay, with silt deposit, free from growth, in average condition deteriorating uneven metal flume with curvatures and debris; very large canals in good condition.	0.020
Small, manmade earth channels in well-kept condition; straight natural streams with rather clean, uniform bottom without pools and flow barriers, carvings and scours of the banks	0.025
Ditches; below average manmade channel with scattered cobbles in bed	0.028
Well-maintained large floodway; unkept artificial channels with scours, slides considerable aquatic growth; natural streams with good alignment and constant cross-section	0.030
Permanent alluvial rivers with moderate changes in cross section, average stage; slightly curing intermittent streams in very good conditions.	0.033
Small deteriorated artificial channels, half choked with aquatic growth, winding river with clean bed, but with pools and shallows	0.035
Irregular curving permanent alluvial stream with smooth bed, straight, natural channels with uneven bottom, sand bars, dunes, few rocks and underwater ditches; lower section of mountainous streams with well developed channels with sediments deposits; intermittent streams in good condition, rather deteriorated artificial channels, with moss and reeds, rocks, scours and slides.	0.040
Artificial earth channels partially obstructed with debris, roots, and weeds; irregularly meandering rivers with partly grown in or rocky bed, developed flood plains with high grass and bushes.	0.067

Table 4. Allowable mean velocities to protect against erosion or scour in channels for various soil and materials

Description	V in m/sec	V in h/min
Soft clay or very fine clay	0.2	40
Very fine or very light pure sand	0.3	60
Very light loose sand or silt	0.4	80
Coarse sand or light sandy soil	0.5	100
Average sandy soil and good loam	0.7	140
Sandy loam	0.8	150
Average loam or alluvial soil	0.9	180
Firm loam, Clay loam	1.0	200
Firm gravel or clay	1.1	220
Silt clay soil, ordinary gravel soil or, clay and gravel	1.4	280
Grass	1.2	240
Coarse gravel, cobbles, shale	1.8	360
Conglomerates, cemented gravels, soft slate, tough hardpan, soft sedimentary rock	1.8-2.5	360-500
Soft rock	1.4-2.5	280-500
Hard rock	3.0-4.6	500-920
Very hard rock or cemented concreted (12.4 minimum)	4.6-7.6	920-15,20

2.7. Soil Nitrogen Dynamics and Nitrogen Uptake

This is very much based on SOIL N model of Johnsson et al. (1987). The following processes (Figure 3) were implemented in SALTMED:

Mineralization, Immobilization, Nitrification, Denitrification, Leaching, Plant N Uptake

Nitrogen input included dry and wet deposition, incorporation of crop residues, manure application, chemical fertilizer application and with irrigation water as Fertigation.

Mineralisation of humus, $N_h(z)$, is calculated as a first-order rate:

$$N_{h\rightarrow NH_4^+}(z) = k_h e_t(z) e_m(z) N_h(z) \qquad (18)$$

where k_h is the specific mineralization constant and $e_t(z)$ and $e_m(z)$ are response functions for soil temperature and moisture, respectively.

$N_{h\rightarrow NH_4^+}$ is in g nitrogen m^{-2} day^{-1}, k_h is in day^{-1}, e_t and e_m are dimensionless, $N_h(z)$ is in g nitrogen m^{-2}.

Decomposition of soil litter carbon, $C_l(z)$, is a function of a specific rate constant (k_l), temperature and moisture.

$$C_{l(d)}(z) = k_l e_t(z) e_m(z) C_l(z) \qquad (19)$$

$C_{1(d)}(z)$ is expressed in g carbon m^{-2} day^{-1}; k_l in day^{-1}, e_t and e_m are dimensionless and $C_l(z)$ is in g carbon m^{-2}.

The relative amounts of decomposition products formed:

$$C_{l\rightarrow CO_2}(z) = (1 - f_e) C_{l(d)}(z) \qquad (20)$$

$$C_{l\rightarrow h}(z) = f_e f_h C_{l(d)}(z) \qquad (21)$$

and

$$C_{l\rightarrow l}(z) = f_e (1 - f_h) C_{l(d)}(z) \qquad (22)$$

are governed by a synthesis efficiency constant (f_e) and a humification factor (f_h). $C_{l\rightarrow CO_2}$, $C_{l\rightarrow h}$ and $C_{l\rightarrow l}$ are expressed in g carbon m^{-2} day^{-1}, $C_{l(d)}$ is in g carbon m^{-2}, f_e and f_h are dimensionless.

From Eqs (19), (21) and (22), net mineralization or immobilisation of nitrogen in litter ($N_l(z)$) is then determined:

$$N_{l\rightarrow NH_4}(z) = \left[\frac{N_l(z)}{C_l(z)} - \frac{f_e}{r_o} \right] C_{l(d)}(z) \qquad (23)$$

Box 6: Soil nitrogen cycle and processes

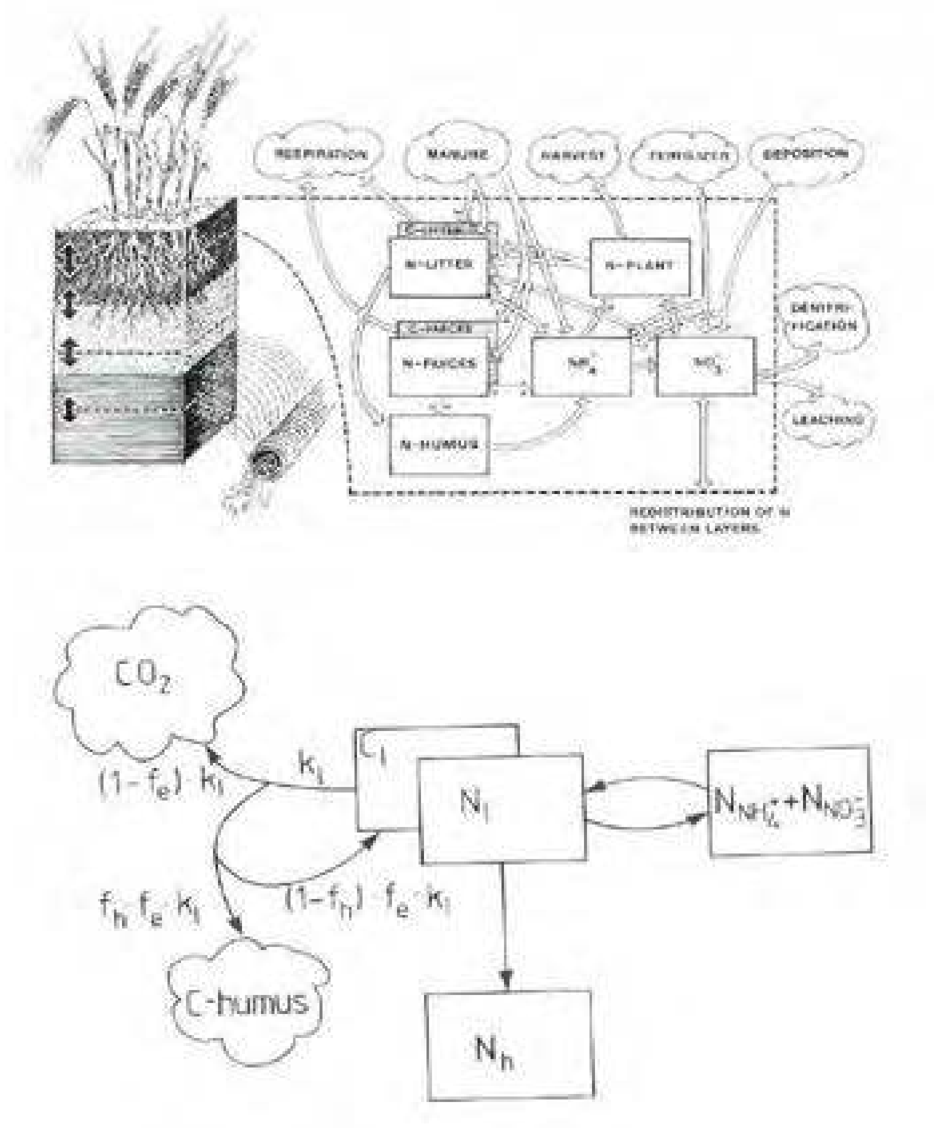


Figure 3. Soil nitrogen cycle and processes according to Johnsson *et al.* (1987)

Where $N_{l \rightarrow NH_4}$ is g nitrogen m^{-2} day$^{-1,}$ N_l is g nitrogen m^{-2}, C_l is g carbon m^{-2}, f_e and r_o (the C-N ratio of microorganisms and humified products) are dimensionless.

The transfer rate of ammonium to nitrate:

$$N_{NH_4 \rightarrow NO_3}(z) = k_n e_t(z) e_m(z) \left[N_{NH_4}(z) - \frac{N_{NO_3}(z)}{\eta_q} \right] \quad (24)$$

depends on the potential rate (k_n) which is reduced as the nitrate-ammonium ratio (η_q) is approached.

$N_{NH_4 \rightarrow NO_3}$ is expressed in g nitrogen m^{-2} day^{-1}, N_{NH_4} and N_{NO_3} are in g nitrogen m^{-2}, k_n is in day^{-1}, and η_q, e_t and e_m are dimensionless.

$$e_t(z) = Q_{10}^{\left[\frac{T(z)-t_o}{10}\right]} \quad (25)$$

where T(z) is the soil temperature for the layer, t_o is the base temperature at which $e_t(z)$ equals 1 and Q_{10} is the factor change in rate with a 10-degree change in temperature.

$$e_m(z) = e_s + (1-e_s)\left[\frac{\theta_s(z)-\theta(z)}{\theta_s(z)-\theta_{ho}(z)}\right]^m \quad \theta_s(z) \geq \theta(z) > \theta_{ho}(z) \quad (26a)$$

$$e_m(z) = 1 \qquad \theta_{ho}(z) \geq \theta(z) \geq \theta_{lo}(z) \quad (26b)$$

$$e_m(z) = \left[\frac{\theta(z)-\theta_w(z)}{\theta_{lo}(z)-\theta_w(z)}\right]^m \quad (26c)$$

$$\theta_{lo}(z) > \theta(z) \geq \theta_w(z) \quad (26d)$$

where $\theta(z)$ is the saturated water content, $\theta_{ho}(z)$ and $\theta_{lo}(z)$ are the high and low water contents, respectively, for which the soil moisture factor is optimal and $\theta_w(z)$ is the minimum water content for process activity. The coefficient e_s defines the relative effect of moisture when the soil is completely saturated and m is an empirical constant. The two thresholds, defining the optimal range are calculated as:

$$\theta_{lo}(z) = \theta_w(z) + \Delta\theta_l \quad (27a)$$

$$\theta_{ho}(z) = \theta_s(z) - \Delta\theta_2 \quad (27b)$$

where $\Delta\theta_1$ is the volumetric range of water content where the response increases and $\Delta\theta_2$ is the corresponding range where the response decreases.

The water content is in m^{3}m^{-3}, soil temperature is in °C and e_t and e_m are dimensionless.

A logistic uptake curve is used to define the cumulative potential N demand during the growing season:

$$\int u(t)dt = \frac{u_a}{1+\frac{u_a-u_b}{u_b}e^{-u_c t}} \quad (28)$$

where u_a is the potential annual N uptake, u_b and u_c are shape parameters and t is days after the start of the growing season, u_a is expressed in g nitrogen m^{-2} season^{-1}.

Daily uptake of nitrate is then calculated from the relative root fraction in the layer (f(z)), the proportion of total mineral N as nitrate and the derivative of the growth curve (u). u is obtained from Eq. 28 on daily basis expressed as gram nitrogen m^{-2} day^{-1}, $N_{NO_3}(z)$ and

$N_{NH_4}(z)$ are in gram nitrogen m^{-2}.

$$N_{NO_3 \rightarrow p}(z) - MIN \text{ of } f_r(z)\frac{N_{NO_3}(z)}{N_{NO_3}(z)+N_{NH_4}(z)}u \quad (29a)$$

And

$$f_{ma} N_{NO_3}(z) \tag{29b}$$

The denitrification rate is expressed as a power function which increases from a threshold ($\theta_d(z)$) and is maximum at saturation ($\theta_s(z)$), where d is an empirical constant

$$e_{md}(z) = \left[\frac{\theta(z) - \theta_d(z)}{\theta_s(z) - \theta_d(z)} \right]^d \tag{30}$$

The denitrification rate for each layer depends on a potential denitrification rate ($k_d(z)$), the soil water/aeration statue ($e_{md}(z)$) and the same temperature factor ($e_t(z)$) used for the other biologically-controlled processes.

$$N_{NO_3 \rightarrow}(z) = k_d(z) e_{md}(z) e_t(z) \left[\frac{[N_{NO_3}(z)]}{[N_{NO_3}(z)] + c_s} \right] \tag{31}$$

$N_{NO_3 \rightarrow}$ (z) and k_d(z) are expressed in g nitrogen m^{-2} d^{-1}, $N_{NO_3}(z)$ is in g nitrogen m^{-2}, C_s is in mg l^{-1}, e_t and e_{md} are dimensionless.

2.8 Calculating soil temperature from air temperature

The top soil layer is the most biologically active layer where most of the organic matter decomposition and mineralization takes place. The microbial activity is affected by the soil temperature of this layer. This temperature was found to be correlated to air temperature. The approach used here is to infer the soil temperature of the top layer (ploughing layer) from the air temperature based on the work of Kang et al. (2000) and Zheng et al. (1993).

For air temperature "A" and soil temperature "T", the relation can be described as:

For $A_j > T_{j-1}(z)$:

$T_j(z) = T_{j-1}(z) + [A_j - T_{j-1}(z)] * \text{Exp}[-z((\pi / (k_s * p))^{0.5}] * \text{Exp}[-k(LAI_j + litter_j)]$ (32)

For $A_j \leq T_{j-1}(z)$:

$T_j(z) = T_{j-1}(z) + [A_j - T_{j-1}(z)] * \text{Exp}[-z((\pi / (k_s * p))^{0.5}] * \text{Exp}[-k(litter_j)]$ (33)

A_j is average Air Temperature at day "j " in °C.

This is calculated from Tmin and Tmax given as input in climate data file.

T_{j-1} (z) is Soil temperature at day "j-$_1$" previous day at depth "z " below soil surface, °C

T_j (z) is Soil temperature at day "j "and depth "z "below soil surface, °C

Exp [-z ((π / (k_s * p))$^{0.5}$] is a damping ratio

k_s is the thermal diffusivity as a function of soil water, air and mineral content, m^2 s^{-1}

k_s = (thermal conductivity/(bulk density* specific heat capacity)).

P: is period of either diurnal or annual temperature variation, z is in meters

LAI: is calculated already in the model on daily basis, Litter fraction is given as user input.

2.9 Multiple and simultaneous model application

The SALTMED model runs with up to 20 fields, treatments, or rotations. This facility allows simultaneous runs of different actual systems of soil, crop, irrigation, N-fertilizers and allows different "what if" scenarios as model application in forecasting / prediction mode. Some of the main model tabs and an example of output are shown in Figure 4 left side.

The model has two tabs, Global Parameters tab, (Figure 4 right side) where parameters are common to all field and not associated with any particular field and Field parameters tab where parameters differ from a field to another. Under the Global parameters (Figure 5), the user can specify the fields or treatments up to 20 fields/treatments, decide on the name and location of the results folder where the model will be recording the results of each field, specify the soil properties of the soil of the study site and specify the crop properties as shown below. Both soil and crop properties are saved into the input database and called within each field tab.

Figure 4. SALTMED model opening frame (left) and global parameters tab (right).

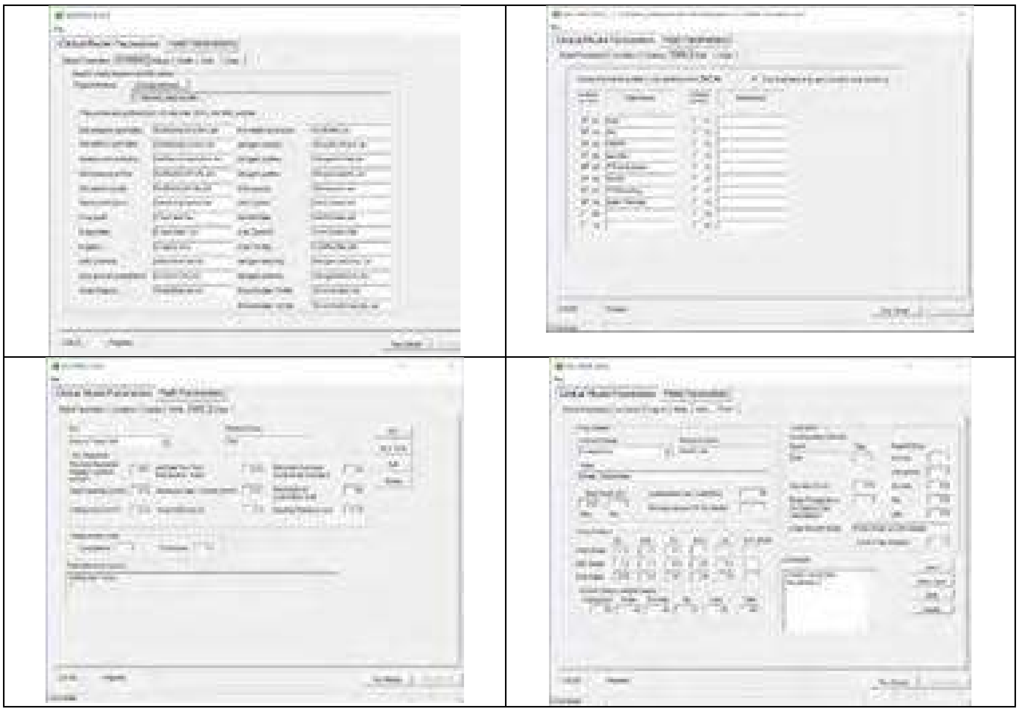


Figure 5. Outputs tab (top left), Fields tab (top right), Soils tab (bottom left) and Crops tab (bottom right).

Example of output:

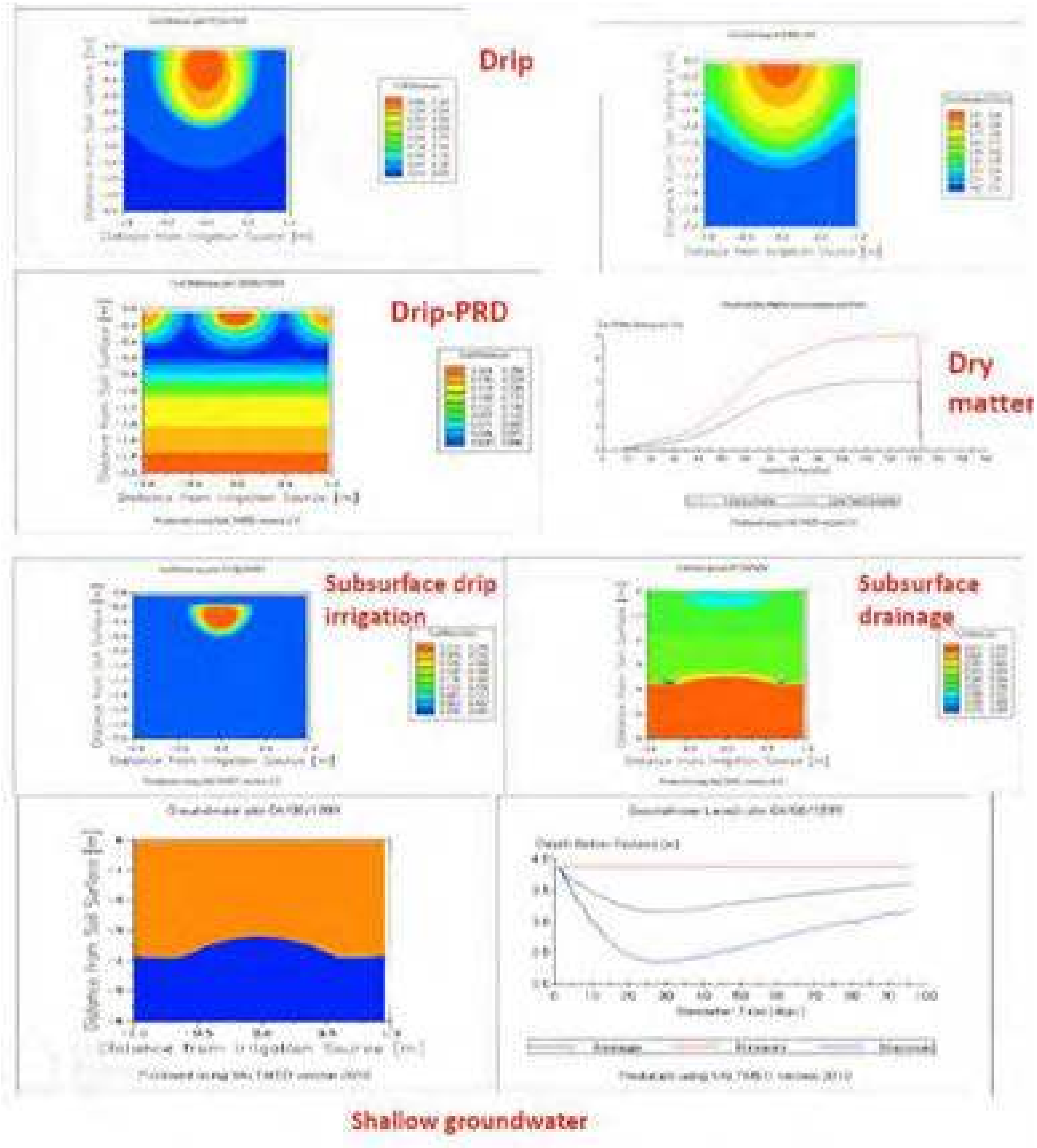


Figure 6. Examples of figure output of SALTMED model.

3. SALTMED input data requirement

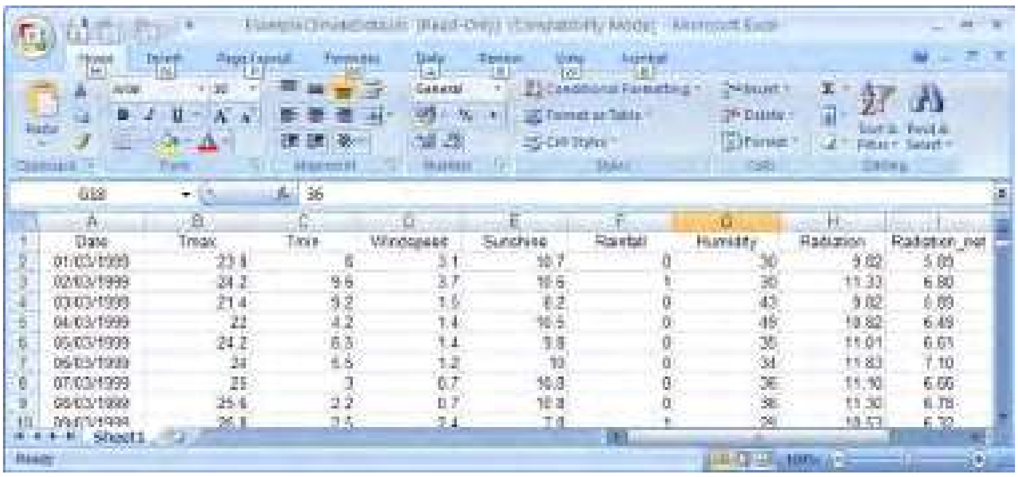
The data required depends on the selected application options and the interest of the user. The user does not need to provide all the information in the model tabs. For example, if no drainage system is present, the user does not need to fill in the data for the drainage tab. The model has more than one option for some applications, such as evapotranspiration, but the user does not need to provide data for all options and can just provide the necessary data and parameters for one evapotranspiration option. In the following sections, the model tabs will be shown and the data requirement for each tab will be highlighted. The model can run with up to 20 different fields or 20 treatments. Each field or treatment will require its own input, there is no input sharing among fields or treatments. The input data for the different model tabs will be discussed starting from left to right.

3.1. The climate data tab

As shown, the **daily data** required is:

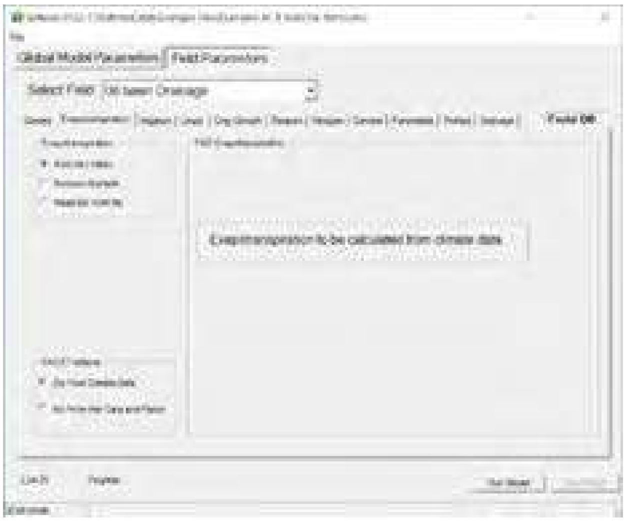
1. Maximum and minimum temperatures in °C
2. Wind speed in meters/seconds
3. Sunshine hours in hours (this is optional if radiation data is not available)
4. Rainfall in mm/day
5. Relative Humidity in %
6. Total solar radiation in MJ/m^2/day
7. Net radiation in MJ/m^2/day

The data are imported from excel file (*.xls or *.xlsx) or from tables of Access database.



3.2. The evapotranspiration tab

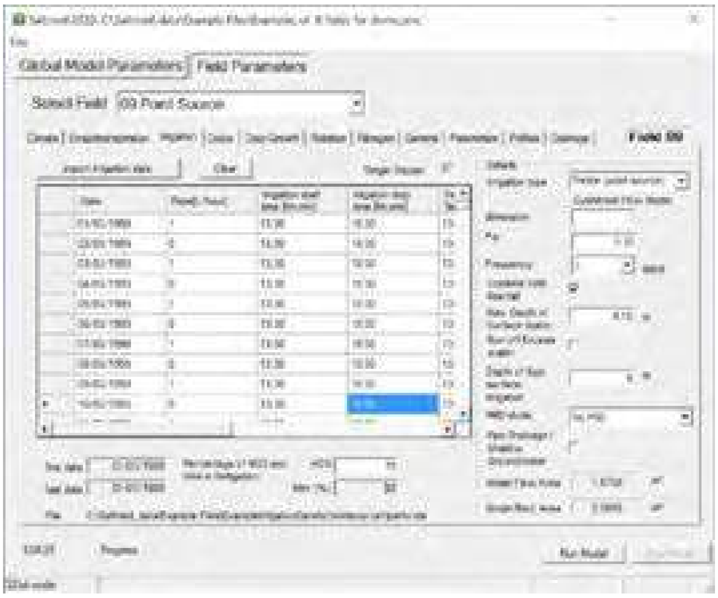
The evapotranspiration is calculated by different methods. The user needs to select only one.

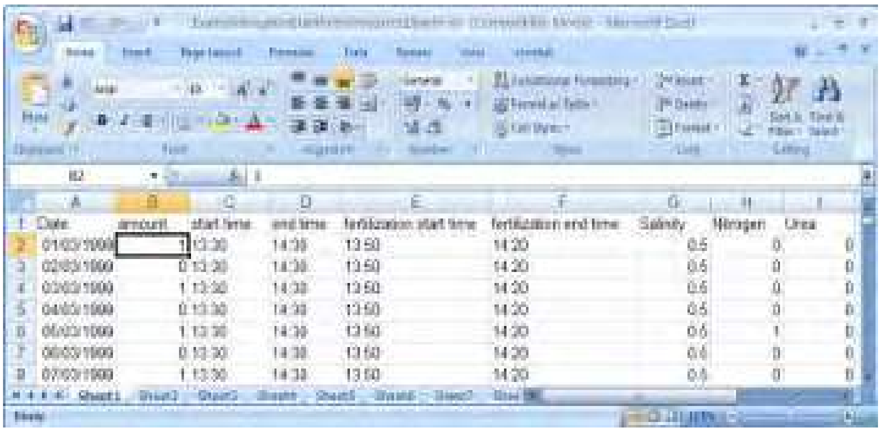


3.3. The irrigation tab

The data required are:

1. Irrigation rate (amount) in litre /hour, except for furrow and trickle line source in litre/meter of line or furrow length/hour.
2. Irrigation start time and stoppage time in format of hours and minutes: hh:mm
3. Fertigation start and stoppage time (if fertigation is used): hh:mm
4. Water salinity in dS/m
5. Nitrogen in water in mg/l, if fertigation is used. If ammonium nitrate is used, specify the % of ammonium to nitrate, as shown at the bottom of the tab.
6. Urea concentration in water in mg/l if urea is used in the fertigation.

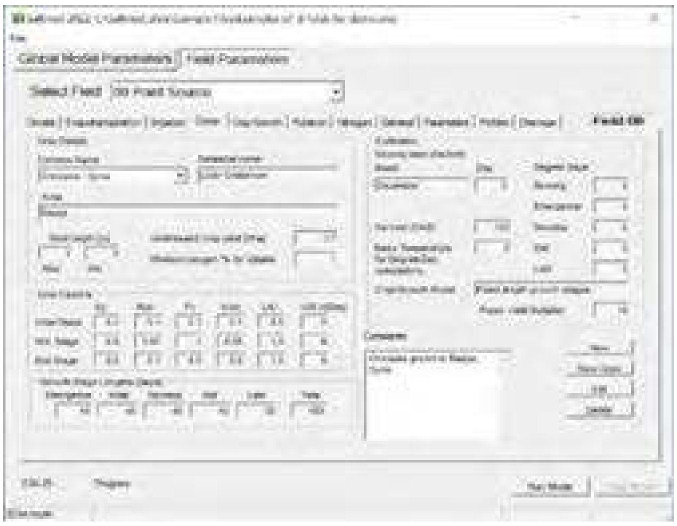




3.4. Crop parameters tab

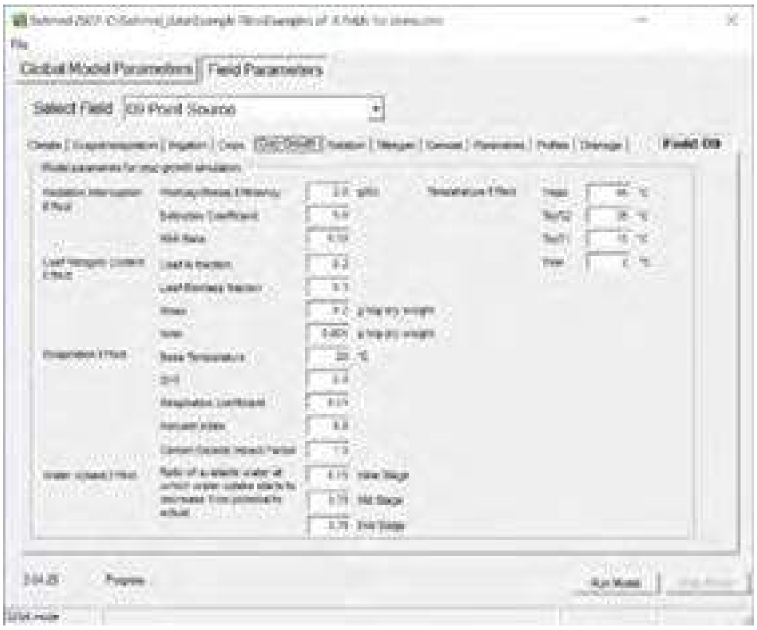
The parameters required are:

1. Minimum and maximum rooting depth in meters
2. FAO-56 crop coefficients Kc, Kcb, fraction cover, Fc for initial, middle and late growth stages. FAO-56 Irrigation and Drainage paper (Allen et al., 1989) provides more information.
3. Crop height in meter, Leaf area index, LAI (total area of leaves in m^2/m^2 of soil area) and π50 (the osmotic pressure at which the water uptake is reduced to 50% of the maximum or potential water uptake) for each growth stage. This is an indicator of crop salinity tolerance. High values mean the crop is more tolerant to salinity; the crop salinity tolerance also varies according to the stage of growth.
4. Duration (days) of initial, development, mid and late growth stages according to FAO-56 (Allen et al., 1989).
5. Sowing date, harvest date, days from sowing to emergency.
6. Minimum basic temperature for growth in °C.
7. Optional: In case the user is interested in using degree days /heat units for crop growth rather than fixed dates, the user will need to input the number of degree days/heat units required to reach each growth stage until harvest. This is useful for those interested in climate change impact on sowing and harvest dates, total biomass and yield, water balance component, nitrogen dynamics, and other relevant output of the model.



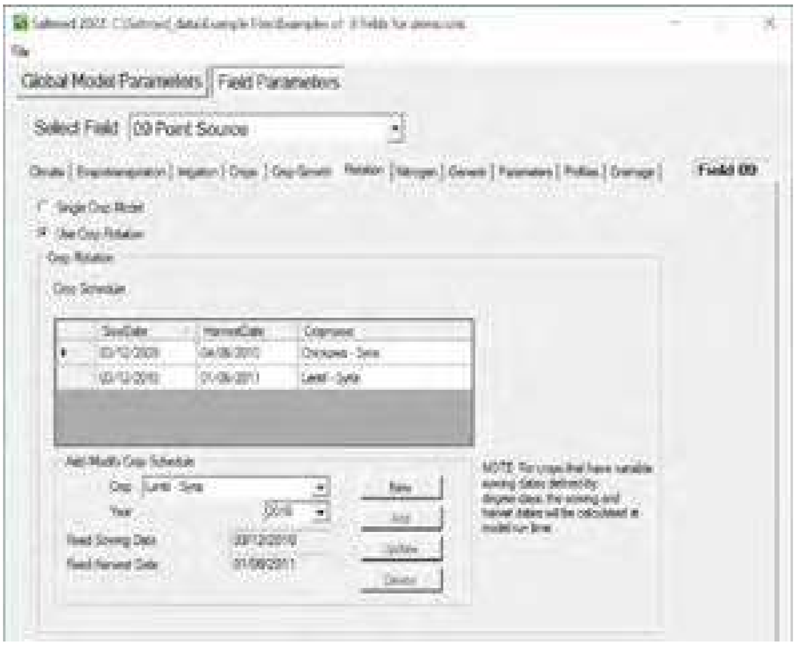
3.5. Crop growth tab

The crop growth is calculated as a function of radiation, photosynthesis efficiency (gram dry matter/MJ radiation), stress factors related to water availability, temperature, Nitrogen content of leaves, respiration losses (%), minimum, maximum and optimum temperatures (°C) for growth. These parameters are obtainable by measurements or from literature or by calibration using the default values as starting values. Measured values are always preferred.



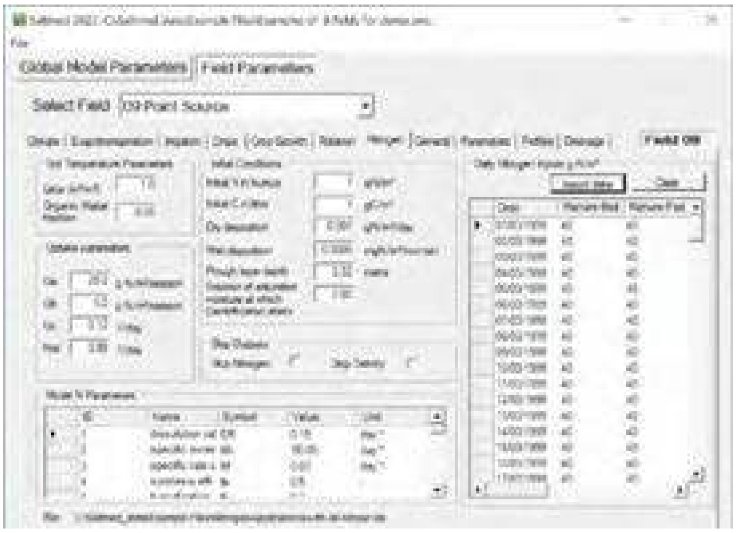
3.6. Crop rotation tab

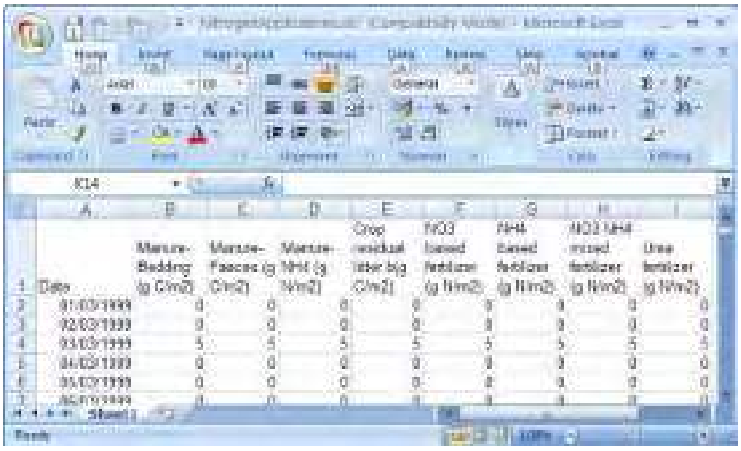
The user can select either single crop or select rotation from the dropdown menu. For rotation, the user needs to select the name of the crop, sowing date and harvest date from the crop database. The crop parameters included in the rotation should have been stored in the database in advance using the crop tab editor under global parameters tab.



3.7. Nitrogen tab

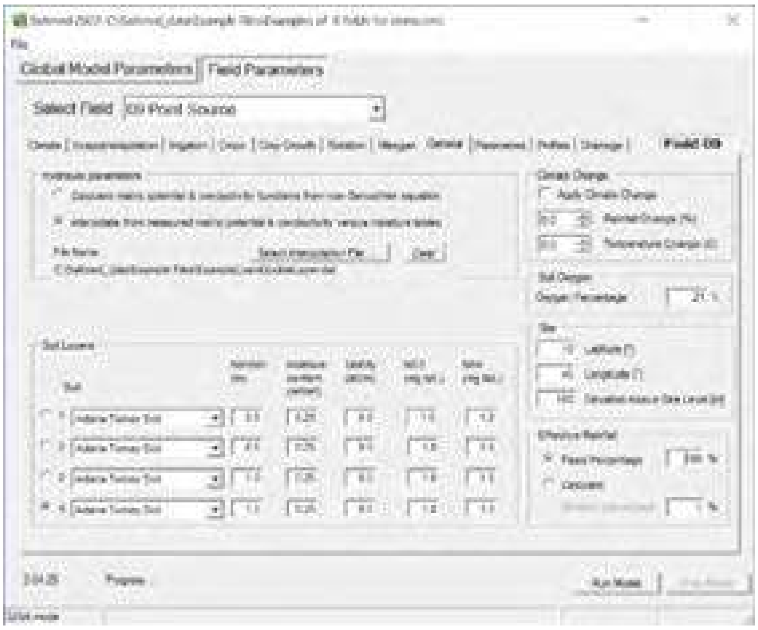
If Nitrogen is added in dry form (organic or mineral), not with irrigation water (fertigation), the user needs to specify the amount of Nitrogen fertilizer in gram N/m^2 of soil surface. The data should be given in an Excel file that includes the date and amount given. The data should be organized using the format of the example file (see below). If Fertigation is used, the user can tick the box of 'skip Nitrogen' without a need to import a Nitrogen file. In addition to daily Nitrogen input, there are other parameters related to Nitrogen uptake by plant, dry and wet atmospheric deposition of nitrogen, initial nitrogen content of soil humus (gram nitrogen/m^2) and initial carbon content in soil litter (gram carbon/m^2 of soil), litter distribution (m^2 litter/m^2 soil) and soil organic matter percent (% of soil mass). In addition, there are other parameters related to rate constants (rate of mineralization, rate of denitrification, etc.), C/N ratios, dissolution rates, etc. are saved in the input database and can be edited through Microsoft Access.





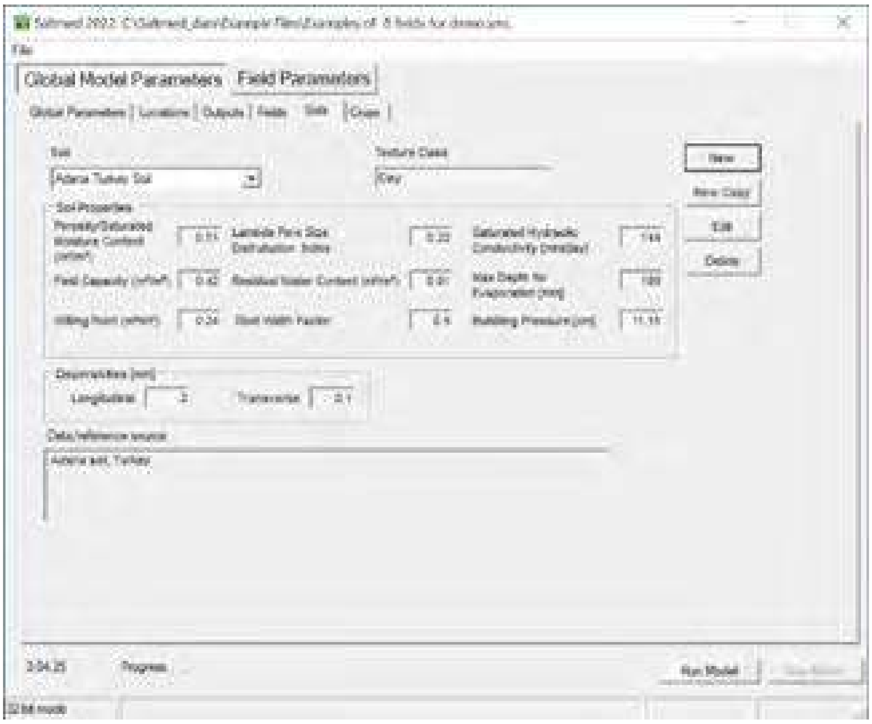
3.8. General tab

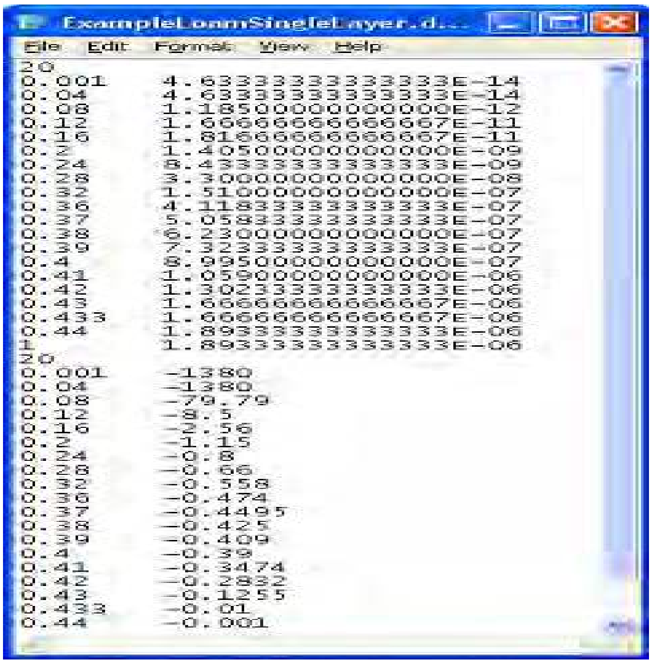
This tab allows the user to specify initial conditions (first day of model run) of soil moisture (m^3 water/m^3 soil), soil salinity (dS/m) soil Nitrate NO_3 (mg N/l) and soil NH_4 (mg N/l) for each soil layer, maximum 4 layers. The thickness of each layer should be given. On the same tab, there are two options to obtain the water retention curve and hydraulic conductivity curve. These two functions can either be calculated from other soil parameters given in soil tab (under global parameters tab) or from measured and tabulated pair values: soil moisture (m^3/m^3) versus water potential (m), and hydraulic conductivity (meter/second) versus soil moisture (m^3/m^3). Examples of these pair values are given in example files folder provided by the model.



3.9. Soil parameters

An example of water retention and hydraulic conductivity measured values to be used in SALTMED is shown hereunder. First row is number of pair values (20), followed by volumetric soil moisture, m^3/m^3 (left) versus hydraulic conductivity, m/s (right), then another 20 values of soil moisture, m^3/m^3, versus water potential (m). This shown data is for a soil of single layer of loam. If more than one layer exists with different water retention and conductivity functions then using the same format, just add the other layers to the same file, one layer after the other (maximum 4 layers), see example files folder provided by the model.



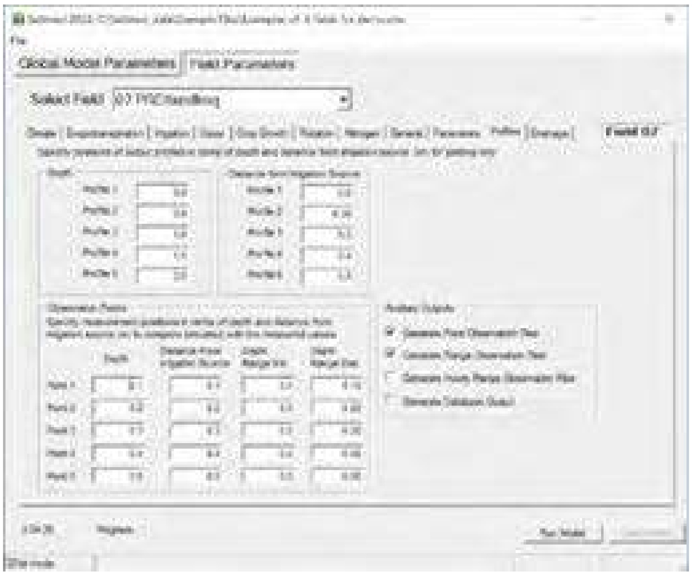


3.10. Parameters tab

This tab includes a number of parameters. Depth and width of the model flow domain and size of each square in the flow domain. The model flow domain is divided into squares with default size of 4 cm by 4 cm. However, the size of flow domain and size of the squares can be changed by the user. The model calculates the flows (water, solute, nitrogen) in each square of the domain. There are other parameters related to solute diffusivity, H_{50}, (the water potential at which the water uptake is reduced to 50% of the potential water uptake), parameters related to Kr which controls the bare soil evaporation as given in FAO-56 (Allen et al., 1989). Apart from the flow domain dimension, which is user input, the other parameters are default values but the user can change these values according to measurements or literature.

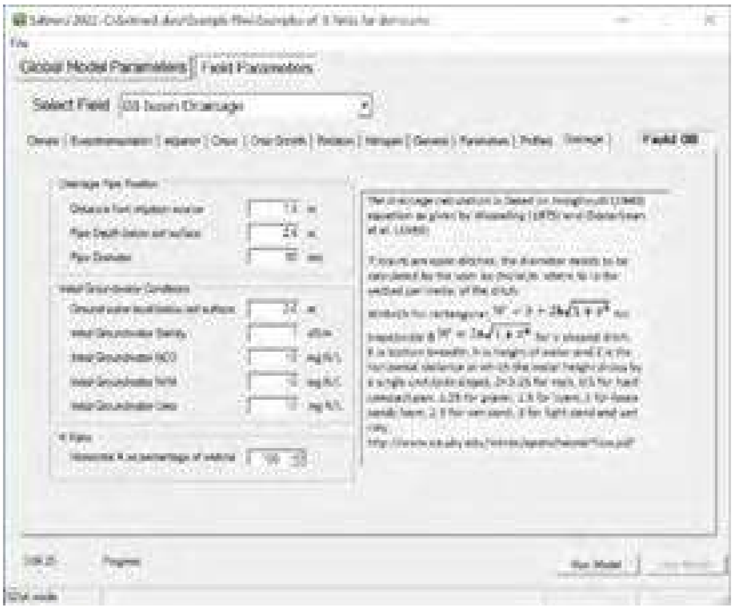
3.11. Profiles tab

This tab allows the user to specify what depth and how far from irrigation source, the soil moisture, soil salinity, soil nitrogen profiles should be plotted in the figures that appear on the computer screen during model run. In addition, the tab allows the user to select how the data should be recorded in the output file in order to compare measured values with simulated values. In such case, the user can request the simulated values to be recorded at the same depth and distance from the irrigation source exactly like the measured values so that, a comparison can be made in minutes using Excel plotting facilities. The user can also request the same variables for certain layers (range values e.g., 0-30 cm, 40-60 cm depth). The user can also request to save output in Access database if running huge data records (decades of years for climate change scenarios), these request options are shown below.



3.12. Drainage tab

This tab can only be used in the case of presence of tile drains, open drains or shallow groundwater. Parameters needed are: depth of drains, their diameters, initial ground water salinity and nitrogen content, ratio of horizontal hydraulic conductivity to the vertical conductivity (given in soil tab).



3.12.1 Pipe Location and Dimensions

The model allows for a single pipe to be positioned within a field, at a specified distance from the irrigation source and depth below the surface (this pipe is mirrored to the other side of the irrigation source). The diameter of the pipe may also be defined.

3.12.2 Initial Groundwater Conditions

It is generally assumed that the soil below the drainage pipe is saturated i.e., it is nominally the groundwater level. For the model to function correctly, the groundwater must not be allowed to act as recharge to the geology below the bottom soil layer since this could result in the soil moisture dropping below saturation, and flow into the pipes would be reduced or stop. To prevent this situation, the bottom of the soil is assumed to be impermeable in the pipe drainage model, and this means that the main exit route for water leaving the model is via the pipe.

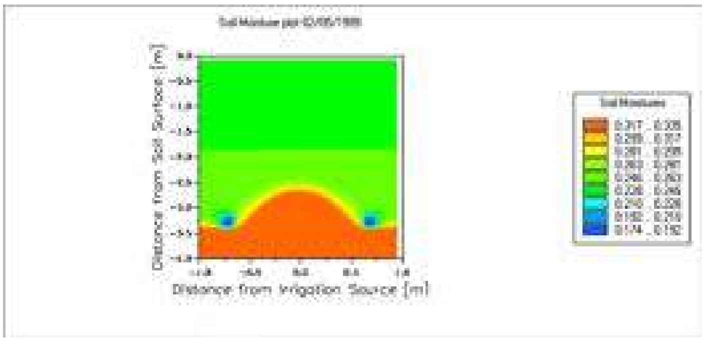
When a model runs with very dry soil it may take many weeks or months for irrigation to saturate the soil below the pipe and reach an equilibrium situation. To short cut this process, the model can be initialized with the groundwater below a specified depth. The means the model will start to function properly much more quickly.

The initial groundwater conditions also allow the specification of initial Salinity, Nitrogen and Urea.

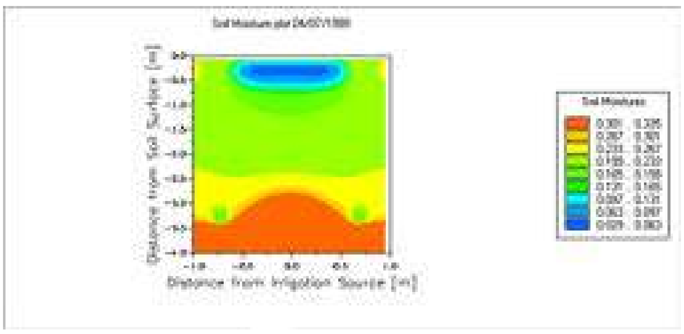
3.12.3. K Ratio

The conductivity of the soil layers may not be the same in the vertical and horizontal planes. The “K Ratio” field allow the horizontal conductivity to be defined as a percentage of the vertical conductivity. In absence of measurements or estimations, as a role of thump, the horizontal may be taken as one third of the vertical conductivity.

A drainage model will normally be expected to exhibit a “dome” in soil moisture rising to approximately half the distance between the two drainage pipes that appear on the output graphs. A typical example is shown below:



The pipe locations can be clearly seen. In the above example we have not used a crop in order to simplify the output. Adding a crop into the model will tend to reduce the moisture values above the “dome”, as illustrated below:



Obtaining this characteristic in a specific model usually requires some fine tuning and repeated running of the model changing one parameter at a time. Some hints to aid this tuning are as follows:

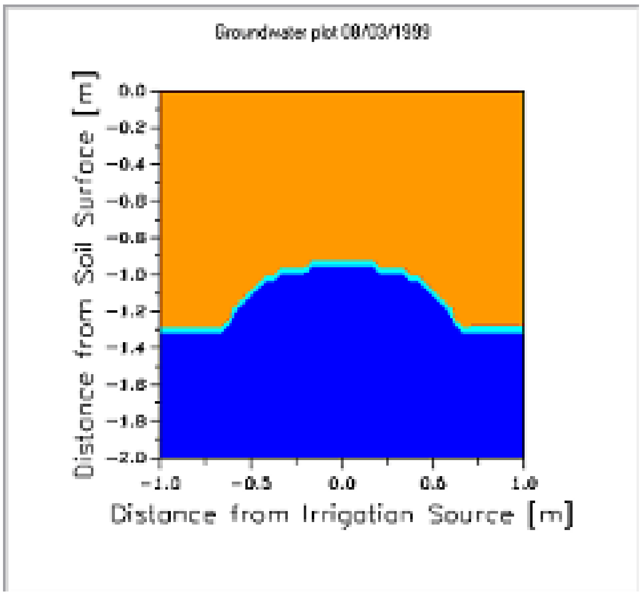
Behaviour	**Possible Cause**	**Parameter to change**
"Dome" collapses to being low or even flat	Horizontal conductivity too high	Reduce "K Ratio" of horizontal conductivity to vertical conductivity
	Irrigation input too low	Increase irrigation via the input irrigation spreadsheets.
	Pipe diameter too big	Reduce Pipe diameter
"Dome" rises too high and overpowers pipes.	Horizontal conductivity too high	Increase "K Ratio" of horizontal conductivity to vertical conductivity
	Irrigation input too high	Reduce irrigation via the input irrigation spreadsheets.
	Pipe diameter too small	Increase Pipe diameter

3.12.4 Enabling Pipe Drainage

For a model to use pipe drainage, it must be enabled via the "Irrigation" panel. Note that this option is only available for 2D and 3D models. This is a requirement in order to view proper moisture plots.

3.12.5. Groundwater Output Plots

As an aid to setting up a pipe drainage model, an output "Groundwater" plot is provided. This does not show absolute moisture levels, but instead shows just which model cells are saturated. An example is shown below:



3.12.6. Shallow Groundwater System

In absence of a pipe drainage system and presence of shallow groundwater, it is possible to simulate a shallow groundwater model using features provided for drainage systems. The method is as follows:

- Set the irrigation tab to use Pipe Drainage/Shallow Groundwater

  This has the effect of making the bottom of the model impermeable and allows groundwater to build up.

- Set the diameter of the drainage pipe to zero.

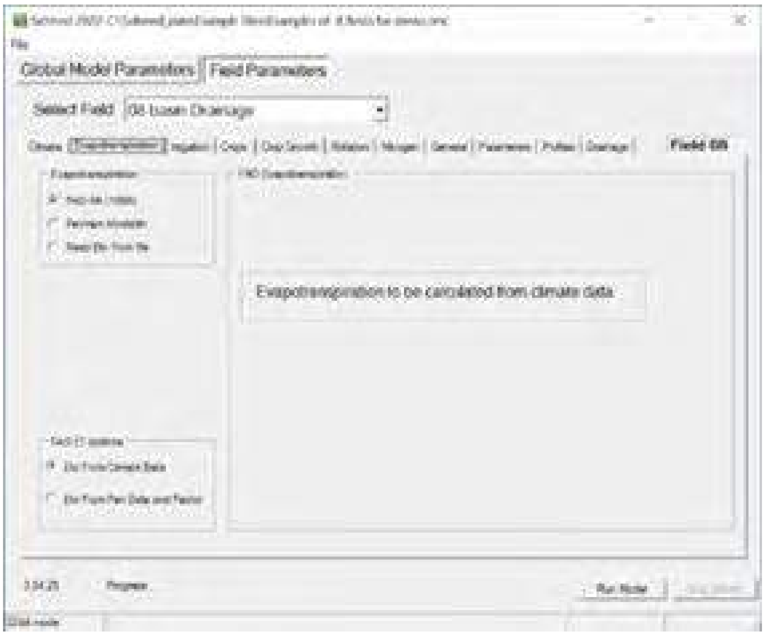
  This means that no water can exit the model via the pipe, and groundwater will rise up and past the pipe location, simulating groundwater.

3.12.7 Limitations to the shallow groundwater option:

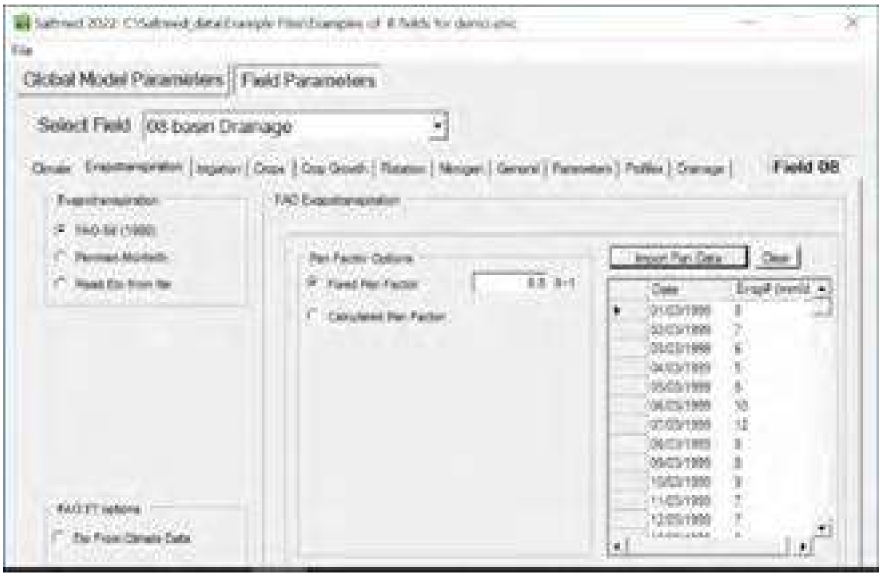
When using the shallow groundwater option, it is possible for the groundwater to rise and saturate the entire soil profile. If this happens, the model will show increased surface runoff (sometimes known as groundwater flooding), since water cannot infiltrate other than to replace evaporation and/or transpiration. Careful control of irrigation input values may be needed to get a model that maintains a groundwater level that is below the surface.

3.13. Evapotranspiration, ET, tab options

Option 1. Calculates the ET using climate data according to the FAO modified Equation of Penman Monteith (assumed stomata conductance of 70 m/s).

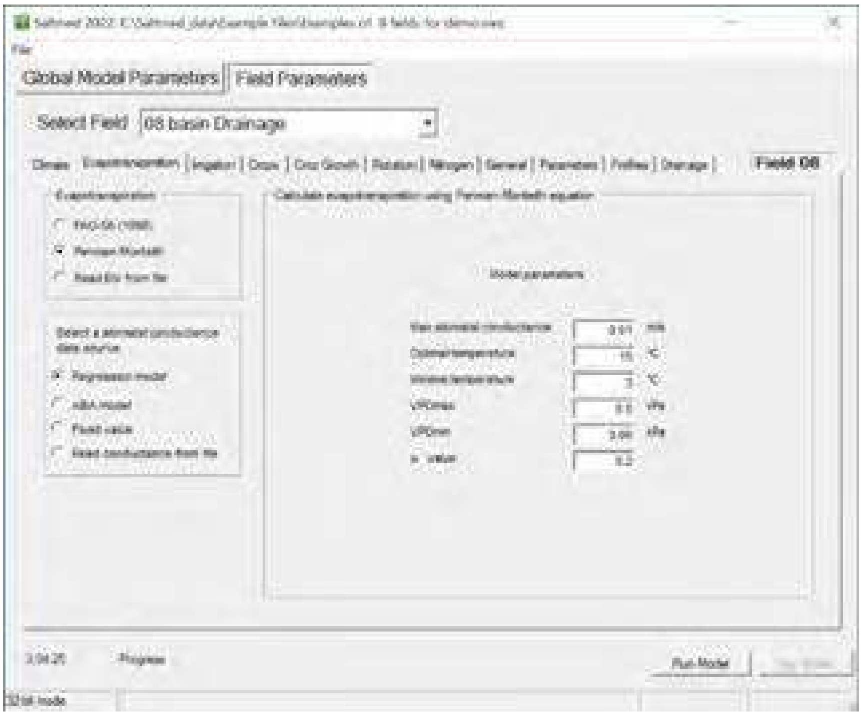


Option 2 Calculates the ET from Class A pan, an excel file containing daily evaporation in mm/day is needed. Class A pan factor can be specified by the user or calculated using FAO formula, see FAO-Irrigation and Drainage Paper No 56 (Allen et al., 1989) for more information.

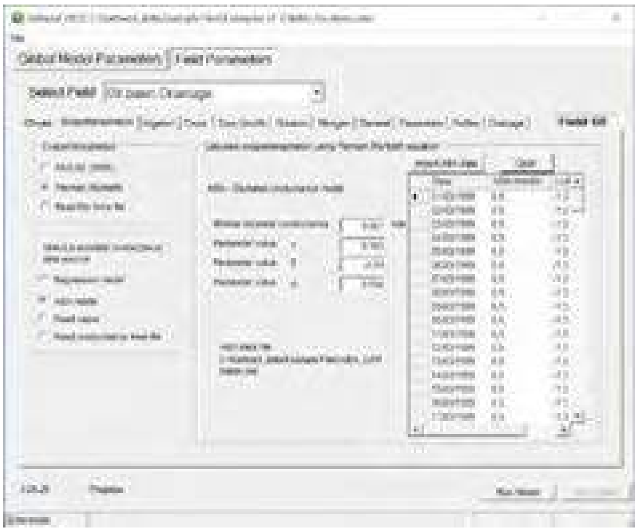


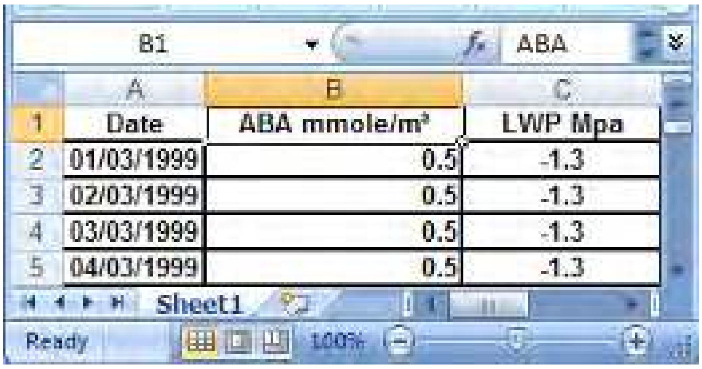
Option 3 is to calculate ET from the **original** Penman Monteith equation, with 4 options to calculate the stomata conductance. This conductance is needed in calculating ET using the original Penman Monteith equation. The four options are:

Calculating stomata conductance from environmental parameters, using a regression model (Jarvis, 1967; Körner, 1994) and some fitting parameters as shown in the dialogue below.

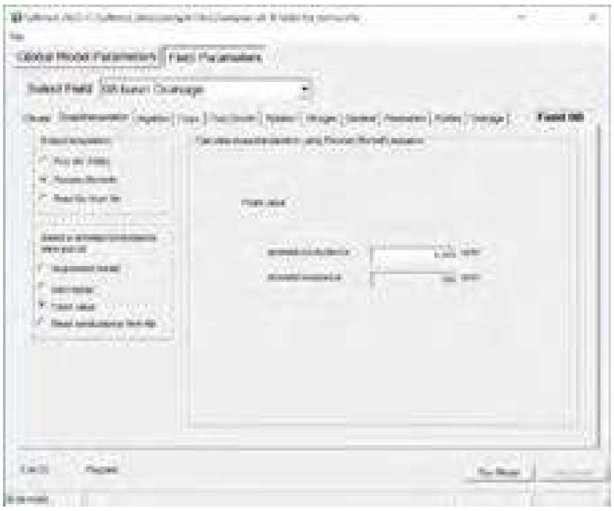


Calculating stomata conductance from daily values of Absecic Acid (ABA) in mmole m^{-3} and leaf water potential in MPa according to Tardieu et al. (1993). Data are provided as Excel file (see example in the example files folder). Other fitting parameters values as suggested by the authors are given as default values in the dialogue below.

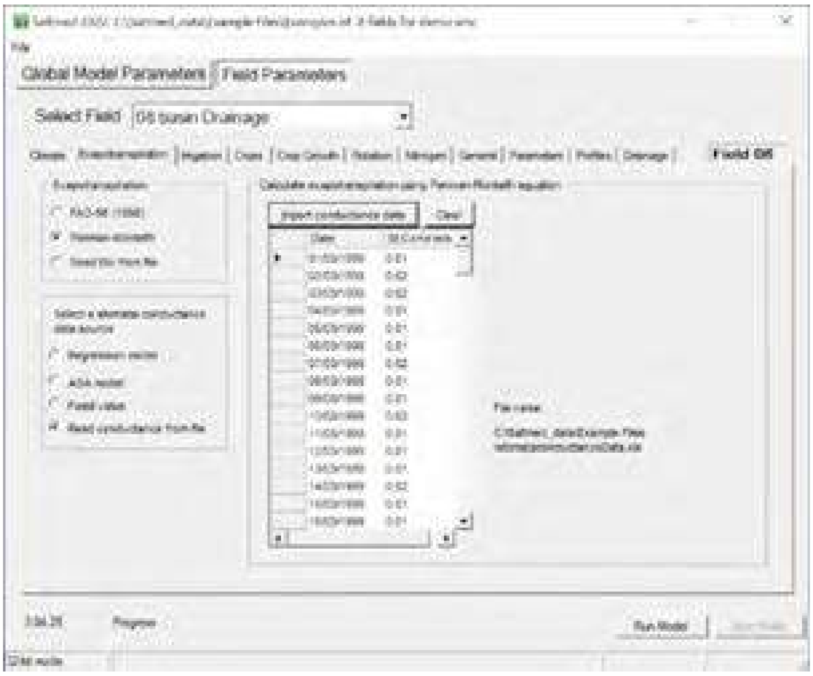




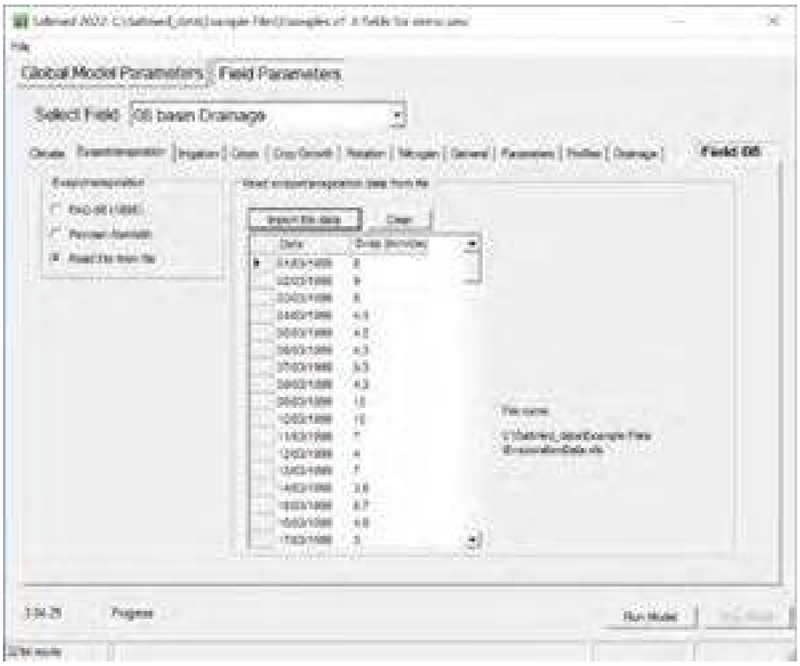
Using measured or estimated seasonal average stomata conductance value as in the dialogue below.



Use daily measured values of stomata conductance. Data are provided in meter/second in an Excel file, see example in the example files folder provided by the model.



Option 4: Use readily calculated or measured Reference ET in mm/day given as excel file. This allows the user to use own measured values or calculated values by other methods or equations different from those used in SALTMED, see example in the example files folder provided by the model.



4. Goodness of Fit' indicators

The SALTMED model performance was evaluated by quantitative (statistical) and qualitative (graphical) methods. In the graphical approach, the measured and simulated values of soil moisture were plotted against time. The response of the model can, therefore, be visually quantified. The statistical approach involved the use of the 'goodness of fit' test proposed by Loague and Green (1991) to compare observed data with results predicted by the model. The 'goodness of fit' indicators are: the root mean square error (RMSE), coefficient of determination (R^2) and coefficient of residual mass (CRM).

The RMSE values show by how much the simulations under or over-estimate the measurements:

RMSE= $\sqrt{\Sigma(yo - ys)^2 / N}$ (32)

where

- *ys*= predicted value
- *yo*= observed value
- N= total number of observations

The R^2 statistics demonstrate the ratio between the scatter of simulated values to the average value of measurements:

$$R^2 = \left\{\frac{1}{N} \quad \frac{\sum(y_o - \bar{y_o})\,(y_s - \bar{y_s})}{\sigma y_o - \sigma y_s}\right\} \qquad (33)$$

where:

- $\bar{y}o$= averaged observed value
- $\bar{y}s$= averaged simulated value
- σyo= observed data standard deviation
- σys= simulated data standard deviation

The coefficient of residual mass (CRM) is defined by:

$$CRM = \frac{(\Sigma y_o - \Sigma y_s)}{\Sigma y_o} \qquad (34)$$

The CRM is a measure of the tendency of the model to overestimate or underestimate the measurements. Positive values for CRM indicate that the model underestimates the measurements and negative values for CRM indicate a tendency to overestimate. For a perfect fit between observed and simulated data, values of RMSE, CRM, R^2, should be equal 0.0, 0.0, and 1.0, respectively. All the analyses were made using Excel (Microsoft Inc.)

5. SALTMED Applications

The model has been calibrated and validated with field data of : drip irrigated tomato and potato crops in Syria, Egypt, Crete, Serbia and Italy (Ragab et al., 2005b and 2015, Afzal et al. 2016), sugar cane using sprinkler irrigation in Iran (Golabi et al., 2009), cotton using drip irrigation in Greece (Kalfountzos et al., 2009), quinoa using saline water in Denmark (Razzaghi, et al., 2011), quinoa, sweetcorn and chickpea using drip irrigation in Morocco (Hirich et al., 2012), vegetable crops in Brazil (Montenegro et al., 2010), quinoa using saline water in Italy (Pulvento et al., 2013), amaranth using saline water in Italy (Pulvento et al., 2015b), rainfed and irrigated chickpea in Portugal (Silva et al., 2013), quinoa under deficit drip irrigation in Morocco (Fghire et al., 2015, 2017), sweet pepper in green houses using saline water in Turkey (Rameshwaran et al., 2015, 2016), legumes (lentil, chickpea and faba bean) using saline water in Syria (Arslan et al., 2016, Ramesh et al., 2016a), quinoa using fresh and saline water in Turkey (Kaya and Yazar, 2016) and potato using gated pipes in Egypt (El-Shafie et al., 2016). In all these studies the model proved its reliability and ability to predict the field measured yield, dry matter, soil moisture and salinity.

The model was also used to derive the salinity-yield response function (Arslan 2016 and Rameshwaran et al., 2015, 2016, 216a) and to predict the impact of climate change on the amaranth and corn water requirement, yield, sowing and harvest dates and the length of the growing season in two countries, Italy and Morocco (Pulvento et al., 2015a and Hirich et al., 2016).

The model has been intensively used in Egypt on a variety of field crops (Abdelraouf and Ragab 2017, 2018a,b,c, Abdelraouf et al., 2020, Dewedar et al., 2021, Marwa et al., 2020, El-Shafie et al., 2017), in Pakistan (Chauhdary et al., 2019, 2020), in Iran (Basiri et al. 2020, Dastranj et al., 2018), in Portugal (Siva et al., 2013, 2017) and in Morocco (Hirich et al., 2012, 2016 and 2020, Filali et al., 2017, Fghire et al., 2015, 2017). More information and applications are published in a special Issue of Journal of Irrigation and Drainage (Ragab 2020).

6. Issues related to Salinity, Measurements, Modelling & Irrigation

6.1 The Field versus Laboratory Measured Salinity

The ECe measured in the laboratory using saturated paste extract, does not represent the salinity of the field. Salinity of the field is associated with a concurrent soil moisture. Both salinity and soil moisture should be measured at the same time and at the same depth.

Models produced soil salinity are associated with a twin value of soil moisture. Model users often make mistakes by comparing the soil salinity of the model with the laboratory salinity measured from the saturated paste extract. Keep in mind that plants grow between the wilting soil moisture content and close to saturated soil moisture content. In that range, salinity goes from low at saturation to high at wilting point.

6.2 Issues Related to Measurements

Variability due to heterogeneity: how representative the point measurements are for an area of various vegetation and soil types. Difficulties in measuring some parameters especially in semi and arid regions (e.g., infiltration, hydraulic conductivity, deep percolation below the root zone, etc.). The instruments technology did not advanced as much as the modelling e.g., point versus area measurements.

6.3 Issues related to the Irrigation Systems for Saline Water Application

Drip irrigation especially the subsurface is best suited. Subsurface keeps higher soil moisture in the root zone, reducing salt concentration of the root zone and improving water uptake and yield. Sprinkler can cause salt accumulation on the canopy and leaf burn in sensitive crops, low nozzles close to the ground would be better. Furrow: planting location is important. However, surface irrigation in general is not recommended.

6.4 Issues related to Management Strategies for Water of Different Salinities

Different waters are blended / mixed in the supply network or altering good and poor quality according to the availability or switching according to the critical stage of the growth. Using the fresh water at the sensitive growth stage (early development stage) and use the saline water at the growth tolerant stage is recommended more than irrigating always with mixed water (fresh + saline).

6.5 I ssues related to Leaching Requirement

When? Only when salt concentration exceeds plant tolerance limit. How? By unavoidable irrigation inefficiency, occasional rain, apply fresh water seasonally (recommended), apply fresh water after each irrigation (not recommended unless there is a great risk for the crop if no leaching considered).

6.6 Issues Related to Modelling

Representation of the physical processes at field scale. Most of models are based on point scale equations. Most models struggle with accounting for heterogeneity in soil and plant cover.

Difficulties in calibration of models especially due to data adequacy/gaps, scale mismatch between model output and measurements. Most of model results do not come with uncertainty bounds.

6.7 Uncertainty in Modelling

Model uncertainty stems from the assumptions, processes descriptions, mechanisms, mathematical formulation, and the numerical scheme. In nature all processes operate simultaneously while in model they do not (they follow an order of execution). If evaporation is calculated after infiltration, expect recharge and soil moisture to be different if the order of calculation was reversed. Linearity exists in some model processes but not in nature where nothing is linear.

6.8 Using the field scale models for salinity management

Agricultural water management models are already in use and able to predict soil salinity at a certain soil moisture content over the time (e.g., SALTMED model, Ragab 2002, 2015, 2017, 2019, Ragab 2020). Salinisation is a slow process and models are useful for long-term predictions. These models once validated, they can be used to predict soil salinity and yield, long-term impact of using saline water on yield and soil productivity, accurate estimation of the leaching requirement, establishing more dynamic yield-salinity response function that accounts for soil and irrigation water salinity combined.

6.9. Non- conventional way to use the models

Using the model to predict missing parameters and difficult-to-measure parameters (i.e., π_{50}, Kcb, Kc, Photosynthesis efficiency, etc.), using the model to predict climate change impact (CO_2, radiation, rainfall, temperature, etc.), using the model for experimental design such as the best crop rotation, tillage level, fertilizer management and scheduling, using the model to estimate the crop water requirement and time to irrigate (scheduling) and using the model to design a program for data collection**.**

7. Tips For Saline Water Management

1. Using saline water requires a suitable irrigation system. Low nozzle sprayers/sprinklers below the canopy, close to the ground and sub-surface drip irrigation are suitable. However, Nano-Drip subsurface irrigation using Ultra Low Drip irrigation systems (flow 0.1 to 0.3 L/h) would be a good option and saves 30% of irrigation water.
2. Leaching should only be considered when the salt concentration exceeds the plant tolerance limit. Leaching can be carried out by unavoidable irrigation inefficiency, occasional rain, and seasonal application of fresh water. Excessive or routine leaching after each irrigation is not recommended as leaching can also leach nutrients, wastes water, and adds extra salt if the leaching water is saline.
3. When two sources of water, e.g., fresh, and saline water, are available alternating use of the fresh water at the beginning of the growth season, as the young crop is sensitive to salinity, followed by irrigating with the saline water at later stage, when the crop less sensitive, is a better management than irrigating with the mix of the two water resources for the whole season.
4. Calibrated and validated models (e.g., SALTMED) can be used as good management tools to predict the long-term salinity impact on soil, plant, groundwater, and leaching requirement without the need to conduct field experiments. They can also be used in a non-conventional way to predict missing parameters and difficult-to-measure parameters (i.e. π_{50}, Kcb , Kc, photosynthesis efficiency, etc.), to predict climate change impact (CO_2, radiation, rainfall, temperature, etc.), produce an experimental design such as the best crop rotation, tillage level, fertilizer management and scheduling, estimate the crop water requirement and time to irrigate (scheduling) and using the model to design a program for data collection.
5. Using the actual evapotranspiration, ET, measured or calculated from equations based on validation against measurements is recommended above the commonly used equations (e.g., Modified Penman Monteith) as they produce potential ET representing the

atmospheric demand not the crop demand for water by using only meteorological data with no plant representation in the equation. The potential ET is higher than the actual ET and will lead to excessive unnecessary waste of water. Accurate estimation of irrigation water requirement is important because irrigating with excessive saline water means, adding more salts, leaching nutrients and fertilizers, decreasing soil and groundwater qualities, decreasing water productivity and water use efficiency and irrigating less area.

6. Land management is important when using saline water for irrigation. Land preparation is important to ensure uniform distribution of irrigation water, infiltration and better salinity control. Subsoiling, chiselling, and ploughing breaks up compaction and improves water infiltration and leaching. Special treatments such as deep ploughing, adding and mixing sand with the soil layer, and addition of organic matter, gypsum or green manure improve soil permeability. Conservative tillage, zero or minimum tillage has advantages as it reduces soil evaporation, increases water availability, reduces surface salinity, increases organic matter, reduces soil erosion, increases nutrient availability, reduces agrochemical use, labour and machinery.

7. The spatial variability and soil heterogeneity make area-based measurements more representative. In situ continuous measurements of both soil moisture and salinity at the same time is more accurate than laboratory methods. The salinity relation with yield or other crop parameters is better described using scaled relations e.g., relative yield vs salinity rather than absolute yield vs salinity.

8. Model Software and document availability

1. SALTMED model (Ragab 2019) can be downloaded from the following links:

   - <http://icid-ciid.org/inner_page/41>;
   - <https://www.ceh.ac.uk/services/saltmed#download>;
   - <https://drive.google.com/file/d/1GHoL0daZYPRb4zn2H4M_oPl_3vlOUKpg/view>

An online course is available at: <https://www.youtube.com/watch?v=JRMeUFzuBYU>.

2. SALTMED Publications in Irrigation and Drainage. Virtual Issues First published: 20 May 2020 Last updated: May 2020. Wiley online Library:

   - <https://onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)15310361.saltmed-publications>.

   ICID webinar on Use of saline water, July 1st 2020 <http://icid-ciid.org/inner_page/131>.

   - Presentation at the Second International Laayoune Forum on Biosaline Agriculture 14–16 Jun 2022 <https://icid-ciid.org/icid_data_web/LAFOBA2022_ppts.pdf>.

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