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IRRIGATION AND DRAINAGE

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Guidelines for Irrigation with Reclaimed Water

August 2025

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International Commission on Irrigation and Drainage (ICID), established in 1950 is the leading scientific, technical, and not-for-profit Non-Governmental Organization (NGO). ICID, 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 half-a-century. 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. The mission of ICID is to stimulate and promote the development and application of the arts, sciences and techniques of engineering, agriculture, economics, ecological and social sciences in managing water and land resources for irrigation, drainage, flood management, for achieving sustainable agriculture water management.

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CONTENTS

FOREWORD

As President of the International Commission on Irrigation and Drainage (ICID), I am both honored and pleased to introduce these Guidelines for Reclaimed Water Irrigation. In a time when water scarcity, population growth, and the unpredictable impacts of climate change are increasingly pressing concerns, the need for sustainable water management has never been more urgent. This document represents a shared vision—a guide for balancing agricultural productivity with environmental responsibility, while addressing critical challenges highlighted in the United Nations Sustainable Development Goals (SDGs), particularly Goal 2 (Zero Hunger) and Goal 6 (Clean Water and Sanitation). It also aligns with ICID's Vision 2030, which aspires to a world where water security is a reality, and poverty and hunger are eliminated through sustainable rural development.

While Earth's surface is predominantly covered by water, only 3% constitutes freshwater resources. Of this limited freshwater supply, merely 1% remains readily accessible for human use, with approximately 70% trapped in ice caps and glaciers and another 29% existing as groundwater reserves. Given that agriculture already accounts for 69% of global freshwater withdrawals and over 3 billion people reside in water-scarce farming regions, simply increasing water extraction is unsustainable. By 2050, This will create a dual imperative: meeting rising food needs while curbing agricultural water demand growth to 10-20% through efficiency innovations.

Against this backdrop, reclaimed water—a resilient, underutilized resource—emerges as a transformative solution. When treated and managed responsibly, it can bridge the gap between water scarcity and food security, while reducing pollution, conserving ecosystems, and bolstering climate resilience. This approach is at the core of ICID's mission to promote sustainable agricultural water management through methods that are economically feasible, socially acceptable, and environmentally sound.

These Guidelines are in direct support of SDG 2's call to "end hunger and promote sustainable agriculture", as well as SDG 6's mandate to "ensure sustainable water management." By integrating reclaimed water into irrigation systems, we do not only safeguard crop yields but also reduce dependence on overexploited freshwater sources. This is especially vital for smallholder farmers and communities in arid regions, where water variability poses a constant threat to livelihoods. Simultaneously, the safe reuse of wastewater advances SDG 6 by curbing environmental degradation and protecting groundwater from contamination.

ICID's commitment to these goals is unwavering. For over seven decades, we have championed innovations in water management, recognizing that sustainability demands both technical thoroughness and inclusive governance. This publication synthesizes global expertise, offering pragmatic strategies for water quality assessment, crop selection, system design, and risk mitigation. It emphasizes that reclaimed water is not merely an alternative—it is a cornerstone of circular economies, where waste is transformed into a valuable resource, and resilience is built into every drop.

Yet, guidelines alone are not enough. Their success hinges on collaboration—among governments, farmers, engineers, and communities. We urge everyone to embrace these principles, adapt them to local needs, and invest in building the necessary capacity. Let's approach every challenge as an opportunity for innovation, every policy as a step toward equity, and every harvest as a reflection of our commitment to sustainability.

I would like to express my deepest appreciation and gratefulness to the experts, researchers, and institutions whose hard work and dedication have made this document possible. Together, we have the opportunity to turn the vision of a water-secure, hunger-free world into reality. The time to act is now.

Dr. Marco Arcieri
President, ICID

PREFACE

Using wastewater or poor-quality water for irrigation is one of the eight technical strategies proposed in the roadmap to 2030 ICID Vision “A water-secure world free of poverty and hunger through sustainable rural development”. Reclaimed water is considered a stable alternative water source for irrigation which is increasingly used worldwide. These guidelines produced by Working Group on Use of Non-Conventional Water Resources for Irrigation (WG-NCWRI), ICID, is the technical approaches for the safe reuse of reclaimed water.

Based on the Working Group on Use of Poor Quality Water for Irrigation (WG-PQW) , WG-NCWRI is was established in 2018 with the mandate to exchange knowledge, experience and data, to prepare comprehensive reviews and prospects, to produce technical manuals, Guidelines or standards for all NCWR including waste water, drainage water and saline/brackish water, to help promote a safe and good management of poor quality water for irrigation, and to minimize the negative impact on human health and the environment.

These Guidelines include seven chapters on introduction, water quality evaluation, crop classification and selection, feasible evaluation of irrigation area, irrigation system design, management considerations, and conclusions. This document also includes the latest research results in the field to facilitate the further development of reclaimed water irrigation.

Lastly, I wish to thank all members of WG-NCWRI and contributors to the Guideline. It is expected that the Guideline will provide irrigation practitioners, officers, engineers, farmers, agricultural managers with latest information. My thanks also go to ICID Central Office, Secretary General Er. Ashwin B. Pandya, Executive Director H. Varma, and Technical Director Er. B.A. Chivate of the for helping with preparing the publication.

Although the Guidelines have been thoroughly reviewed and revised, some oversights or imperfections may still remain due to the limitations of our knowledge and expertise. We therefore welcome constructive feedback and suggestions from readers, which will be invaluable in further improving and refining this work.

Dr. Wenyong Wu
Chair, ICID Working Group on Use of Non-Conventional Water
Resources for Irrigation (WG-NCWRI)

ACKNOWLEDGEMENTS

The Guidelines for Reclaimed Water Irrigation, developed by the International Commission on Irrigation and Drainage (ICID), provide comprehensive guidance on the utilization of reclaimed water for irrigation purposes. This publication is grounded in data and insights drawn from scientific research and extensive pilot projects on reclaimed water irrigation conducted globally. We extend our sincere gratitude to all individuals who have contributed valuable information and data to this work.

We would also like to express our appreciation to the ICID team. These Guidelines were initially proposed by the Working Group on the Use of Non-Conventional Water Resources for Irrigation (WG-NCWRI) of ICID, with the aim of addressing the challenges associated with reclaimed water irrigation. The primary drafting of the Guidelines was led by Dr. Wenyong Wu, Chairman of WG-NCWRI and professor at the China Institute of Water Resources and Hydropower Research (IWHR), who also served as the chief editor of this publication. Prof. Dr. Ragab Ragab, Honorary President of ICID, founder of this Working Group, Fellow-Principal Hydrologist and Water Resources Management Specialist at the UK Centre for Ecology and Hydrology (UKCEH), UK, provided invaluable technical support throughout the entire process.

Lastly, we wish to convey our deepest appreciation to the members of the Working Group and our colleagues who generously shared their professional expertise and insights, making this book both practical and engaging. The following members of Editorial Board provided significant support in drafting and reviewing the content.

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1. Introduction

1.1 Objectives of the Guidelines

There are several reasons to draft the Guidelines. Reclaimed water irrigation (RWI) has expanded greatly over the past few decades. Globally, the WHO and FAO have released the relative Guidelines in the 1990s and 2000s, and USEPA updated its guideline in 2012, which paid more attention to water quality criteria, crop selection, etc. The objectives of the Guidelines are to work out a systematic technical document in the planning, design and management for decision makers, officers, designers, managers and farmers, by including the new advances in recent years and the new successful modes which could be used as reference for different irrigation scenes.

1.2 Overview of the Guidelines

The guidelines are divided into seven chapters. The emphases of each chapter are listed in Table 1.1.

Table 1.1 Structure of Guideline for RWI

Chapter	**Overview of Contents**
Chaper 1- Introduction	The first chapter introduces the objectives and outline of the Guidelines.
Chapter 2- Water Quality Considerations	This chapter reviews the water quality Guidelines and standards related to reclaimed water irrigation of different countries and international organizations, and analyzes organic and nutrient parameters, inorganic parameters, heavy metal parameters, hygiene and sensory parameters in these Guidelines and standards. Guidelines of water quality parameters are proposed for the safe reuse of reclaimed water.
Chapter 3- Crop classification and selection	This chapter reviews different crop classifications adopted by international standards. It introduces the fate and migration of heavy metals and emerging organic pollutants in soil-plant system. Mathematical models are established to calculate reclaimed-water-irrigation-related health risks for adults and children. Crop classifications of A, B and C are proposed based on potential risks.
Chapter 4- Feasibility Evaluation of Irrigation Area	This chapter provides two methods to evaluate groundwater pollution risks for feasible mapping under reclaimed water irrigation. A contamination risk model is established to evaluate the feasibility of irrigation area. Multi-parameter method is used to evaluate groundwater vulnerability for feasible allocation of irrigation area. The engineering construction requirements are given according to different allocations.
Chapter 5- Irrigation system design	This chapter introduces the general layout of projects, design considerations for different irrigation methods, water transportation and distribution, storage requirements, and exposure control. Due to the difference between RWI and freshwater irrigation, the demand for contamination control and clogging prevention has been taken into consideration when setting up the design specifications.
Chapter 6- Management Considerations of Irrigation system	This chapter introduces the maintenance of irrigation methods, relocation, distribution, and storage. It explores how to calculate and manage the input load of different fertilizers when reclaimed water is rich in nutrients. Salinity control measures should be taken in the case of high-salinity reclaimed water irrigation. Monitoring frequencies and parameters should be considered to control health and environmental risks in operation.
Chapter 7- Conclusions	This chapter highlights the summaries and characteristics of the Guidelines

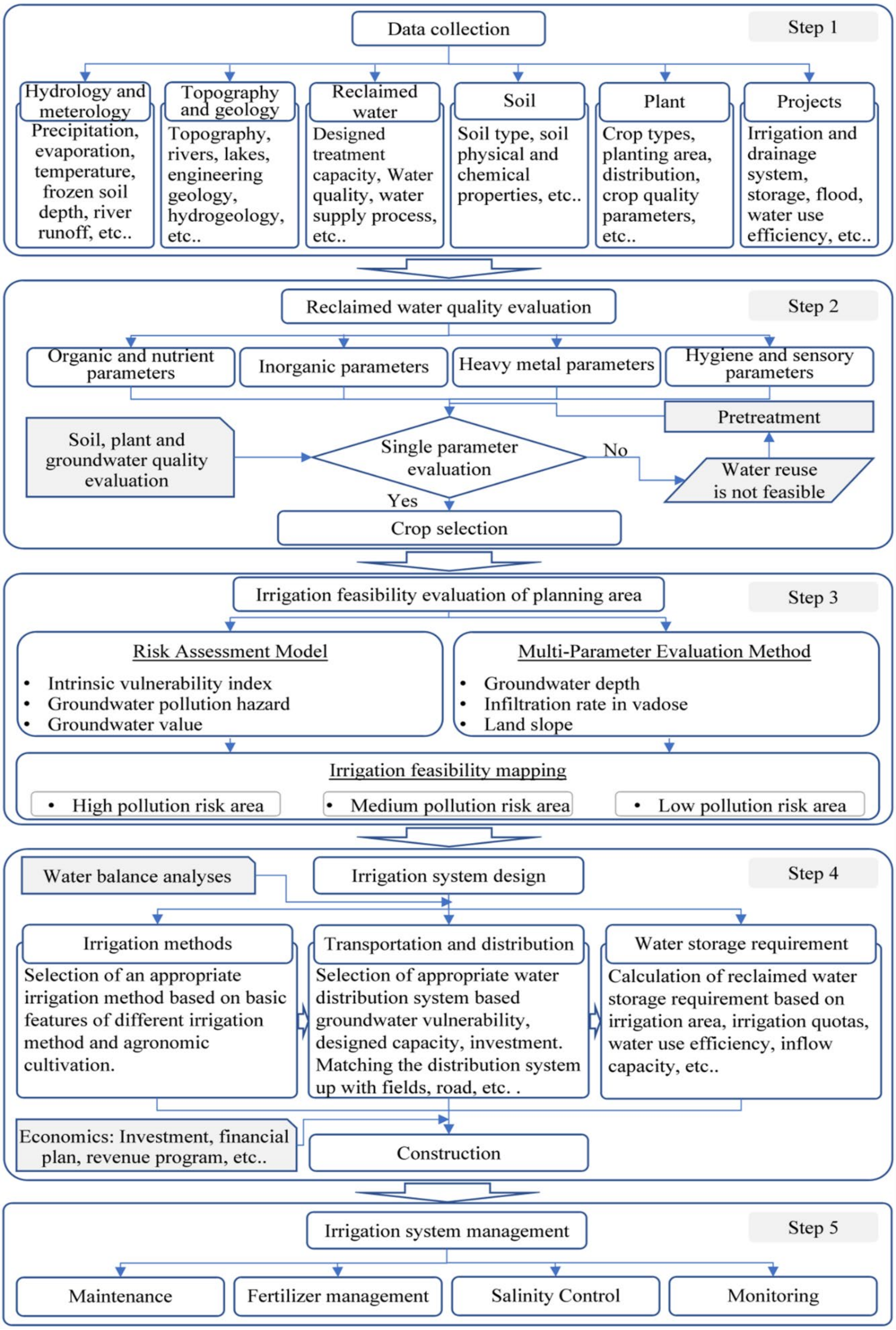


Figure 1.1. Technical chart of reclaimed water irrigation (***Source**: Author's own elaboration)*

1.3 Motivations for the Reuse of Reclaimed Water in Agriculture

1.3.1 Water Scarcity

Nearly 70% of the global freshwater withdrawals is used for agriculture irrigation (Wu et al., 2020, Shahriar et al., 2021). In other words, the agricultural sector is the largest global consumer of water (FAO, 2017; Leonel and Tonetti, 2021). Meanwhile, the global reclaimed water capacity is estimated to have risen from 1.23×10^{10} m^3 in 2010 to 1.99×10^{10} m^3 in 2015 (Chen et al., 2013; Voulvoulis, 2018). The reuse of reclaimed water for agricultural irrigation is an effective way to deal with water crisis (Parsons et al., 2010, Wu et al., 2020).

1.3.2 Environmental Protection

The positive environmental benefits of the reuse include reducing nutrient load to the receiving water bodies, downsizing fertilizer applications, cutting energy consumption and thus carbon emission. It is estimated that irrigation with reclaimed water would provide 16-62 kg of total nitrogen, 4-24 kg of phosphorus and 2-69 kg of potassium per hectare at an application rate of 100 mm (Lazarova and Bahri, 2004). Field irrigation reusing nutrients in reclaimed water could reduce eutrophication and remediate water environment of the receiving water bodies. RWI brings emerging contaminants such as Pharmaceuticals Personalcare Products (PPCPs), Nonylphenol (NPs), etc. into the soil ecosystem, which helps promote degradation and reduce hazards (Hu et al., 2021). RWI saves energy and recycles resources to realize the concepts of planning and management of energy-wise water sector (EPA, 2012).

1.4 Reuse Considerations of Irrigation System

To launch a reclaimed water irrigation project, a lot of factors have to be considered in the process of project planning. First, the evaluation of water quality is very important, given the importance of parameters such as the organic and nutrient level, besides the inorganic, the presence of heavy metal, and the hygiene and sensory characteristics. Second, carrying out a proper feasibility evaluation of the planned area could help prevent environmental pollution caused by percolation and runoff. Third, the layout of storage, distribution and irrigation system should be compatible with crops, fields, roads and groundwater vulnerability.

* * *

2. Water Quality Considerations

2.1 International Water Quality Standards

Many organizations and countries have promulgated laws, regulations, Guidelines and standards for reclaimed water irrigation.

U.S. Environmental Protection Agency issued *Guidelines for Water Reuse* in 2004, and updated it in 2012 (EPA, 2004; EPA, 2012). At the same time, some states in the United States have also issued relevant legal provisions, such as *the California Water Recycling Criteria*, *the Reuse of Treated Wastewater Guidance Manual* of Pennsylvania, and *the New Hampshire's Land Treatment and Disposal of Reclaimed Wastewater* (EPA, 2004; EPA, 2012). Australia published *the Australian Guidelines for Water Recycling: Managing Health and Environmental Risks* in 2006 (EPHCA, 2006). Russia enacted *SanPiN 2.1.7.573-96 Hygienic Requirements to Wastewater and Sewage Sludge Use for Land Irrigation and Fertilization* in 1996 (MHR, 1996).

The EU has long begun to regulate wastewater reuse, mostly through legal provisions. The EU has also been exploring uniform standards and regulations. In 2018, it issued a draft *Regulation of the European Parliament and of the Council on Minimum Requirements for Water Reuse*, and issued an official document in 2020 (EP & CEU, 2018; EP & CEU, 2020). Many EU countries have also issued relevant standards. For example, Cyprus issued *No. 106(1)/2002, the Water Pollution Control Act 2002*, based on which it later introduced *Decree No. 296/03.06.05, General Conditions for Disposing of Waste from Municipal Wastewater Treatment Plants* in 2005 (MANREC, 2002; MANREC, 2005). France issued *Regulations on the Reuse of Irrigation Water for Agriculture and Green Space* in 2010 and updated it in 2014 (MSAPHF, 2010; MSAPHF, 2014). Greece issued *KYA673/400/199, No. 5673/400 Measures and Conditions for Processing Municipal Wastewater* in 2002, and *FEK B 354/08-03-2011, DECISIONS No.co.145116, Determination of Measures, Conditions and Procedures for the Reuse of Treated Wastewater and Other Provisions* in 2011 (MEECCG, 2002; MEECCG, 2011). Italy issued *the Regulating Technical Standards for Wastewater Reuse* in 2003 (MEI, 2003). Portugal issued *the Guidelines for Good Practice of Water Reuse for irrigation: Portuguese standard NP 4434* (IQP, 2005). Spain issued *Spanish Regulations for Water Reuse, Royal Decree 1620/2007* in 2007 (ASERSA, 2007), etc.

China issued the national standard *GB 20922-2007, the Reuse of Urban Recycling Water—Quality of Farmland Irrigation Water* and *GB/T 25499-2010, the Reuse of Urban Recycling Water—Water Quality Standard for Green Space Irrigation* (AQSIQ, 2007; AQSIQ, 2010). Israel enacted *the Public Health Ordinance: Effluent Quality Standards and Rules for Sewage Treatment* in 2010, which has replaced the 1992 regulations on wastewater treatment (WAI, 2010; WAI, 1992). Japan issued *Guidelines for the Reuse of Treated Wastewater* in 2005 (MLIT, 2005). Jordan issued *JS 893:2006 Water—Reclaimed Domestic Wastewater* in 2006 to replace *JS 893:2002 Water –Reclaimed Wastewater* (ISMJ, 2006, ISMJ, 2002). Saudi Arabia enacted *Treated Sanitary Wastewater and Its Reuse Regulations* in 2000 (MOWE, 2000).

The World Health Organization published *WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater* in 2006 (WHO, 2006).

Based on the comparison and analyses of the international guidelines and standards, the aforementioned parameters can be classified into four groups: organic and nutrient parameters, inorganic parameters, heavy metal parameters, hygiene and sensory parameters.

2.1.1 Organic and Nutrient Parameters

The parameters of organic and nutrients mainly include Biochemical Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), Anionic Surfactants (LAS), Total Phenol (TPh), Volatile Phenol (VPh), Pentachlorophenol (PCP), Chloral, Tetrachloroethylene (PERC), Total Chlorinated Solvents (TCS), Total Aldehydes (TAI), Acrolein, Formaldehyde (FORMALD), Trichloromethane (Sum of concentrations, TTHM), Total Aromatic Solvents (TAS), Benzo(a)pyrene [B(a)P], Benzene, Total Phosphorus (TP), Total Nitrogen (TN), Ammonia Nitrogen (NH4+), Total Organic Nitrogen Solvents (TONS), Fat Oil and Grease (FOG), Petroleum (Petro.), and Pesticides etc. Most countries have set limit values of BOD, and parameters such as COD, DO, LAS, nitrogen and phosphorus are also usually involved.

BOD, COD and DO are comprehensive parameters of organic pollution in water bodies. BOD reflects the degree of organic pollutants that can be degraded by microorganisms, and higher BOD values indicate higher organic content and worse pollution in water (Xu and Wang, 2018; Zhang and Yang, 2011). COD indicates the degree of organic pollution in a water body by measuring the oxygen produced from the oxidation of organic matter as exerted by means of strong chemical oxidants (Wang and Wang, 2022). DO reflects the self-purification ability of a water body (Wu et al., 2020). Currently, many standards use five-day biochemical oxygen demand (BOD_5), and COD and DO can be considered as additional parameters to supplement the measurement of organic pollution.

Common nitrogen and phosphorus parameters include TN, Kjeldahl Nitrogen, NH_4^+, Nitrate Nitrogen (NO_3^-), Elemental Phosphorus, TP, etc. As important nutrients, nitrogen and phosphorus play an important role in the growth and development of crops. Nitrogen promotes plant growth through long-term effects (Liang et al, 2021). Phosphorus plays a role in photosynthetic reactions, cells energy transfer and respiration (Marschner, 2012; Fernandes et al., 2015). Excessive intake of Nitrogen and Phosphorus will also have certain adverse effects on crops, such as affecting the population structure of cotton fields, and leading to premature aging of hybrid bolls and reduced yield of hybrid cotton (Yang et al., 2020).

In the current water quality monitoring results of most countries, the contents of LAS basically meet the water quality standards, and occasionally exceed the standard in some months and water bodies. LAS is the product of washing liquid, washing powder and detergent commonly used in people's household. Therefore, the catering and hospitality industry, and the practices of car washing and road construction are the most likely sources of LAS pollution. Relevant limit values should be set according to the water sources. The LAS limit values in some current reclaimed water irrigation standards are outdated and overly conservative compared to the monitoring data (Tang et al., 2016; Mao et al., 2021; Uning et al., 2022). It could be cancelled in most cases.

Petroleum, Phenols, Chloral and Benzene mainly come from industry. Their presence in reclaimed water is limited, but as the pollutant types involved are increasing with technological development, more research and evaluation are needed.

2.1.2 Inorganic Parameters

The inorganic parameters mainly include Total Dissolved Solids (TDS), Chloride (Cl), Chlorine Residual (Cl_2 res.), Boron (B), Fluoride (F), pH, Sodium Adsorption Ration (SAR), Total Water Hardness (TWH, calculated as $CaCO_3$), Electrical Conductance (EC), Magnesium (Mg), Calcium (Ca), Sodium (Na), Phosphide (P, include PO_4), Sulfide (S), Hydrogen Sulfide (H_2S), Sulfur trioxide (SO_3), Sulfate (SO_4^{2-}), Hydrogen carbonate (HCO_4^-), Selenium (Se), Aluminum (Al), Lithium (Li), and Cyanide (CN).

Among them, the comprehensive parameters are TDS, pH, SAR, TWH and EC. TDS and EC are proportional to the ion content and reflect the cleanliness of the water body. pH reflects the acidity of water which has a great impact on both crop growth and metabolism and soil microbial activity. Different standards give slightly different pH limits, for example, 6.0-9.0 in the US, around 5.5-8.5 in Japan and China, and 6.5-8.5 in Israel. pH limits should be stricter, considering the potential salinization of soil brought about by long-term irrigation with reclaimed water and the relevance of pH to the concentration of heavy metals or other substances (EPA, 2012).

SAR and TWH mainly measure the content of Na^+, Ca^{2+} and Mg^{2+}. The increase of irrigation water hardness may cause pipe blockage and affect work efficiency and equipment life (Tamiru et al., 2020; Jia et al., 2020). Also, it may cause environmental problems, such as an increase in groundwater hardness. Hardness may be related to heavy metal plasma content, and there may be some seasonal fluctuations (Yesilnacar et al, 2008; Tamiru et al, 2020; İlhan et al, 2022). Currently, there are few studies on the risk assessment of TWH in reclaimed water irrigation. Relevant research should be encouraged, and strict supervision should be carried out in areas with high hardness.

In water treatment, chlorine or chlorine dioxide are often used as disinfectants. If the residual chlorine exceeds the standard, the water will have an irritating smell. The residue may also react with other organic substances in the water, causing harm to human health; therefore, setting a limit for the residual chlorine is necessary.

Table 2.1. Comparison of organic and nutrient index of reclaimed water irrigation water quality in various countries

CY. / ORG.	Classi-fication	Parameters (mg/L, except for markings)																					
		BOD$_5$	COD	DO	LAS	TPh	VPh	PCP	Chl-oral	PERC	TCS	TAI	Acrolein	FORMALD	TTHM	TAS	B(a)P	Benzene	TP	TN	NH$_4^+$	TO-NS	FOG	Petro.	Pesticides
EU (EP & CEU, 2020)	A	≤10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	B/C/D	≤35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
USA (EPA, 2012)	Urban reuse (Unrestricted)	≤10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Urban reuse (Restricted)	≤30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Agri. Reuse (Food Crops)	≤10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Agri. Reuse (Processed Food Crops/Non-Food Crops)	≤30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Japan (MLIT, 2005)	Sprinkling water	≤20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
China (AQSIQ, 2007, MWRC, 2007, AQSIQ, 2010, AQSIQ, 2020)	Farmland (Fibre crops)	100	200$^{2)}$	≥0.5	8.0	-	1.0	-	0.5	-	-	-	0.5	1.0	-	-	-	2.5	-	-	-	-	-	10	-
	Farmland (Dry grain)	80	180$^{2)}$	≥0.5	8.0	-	1.0	-	0.5	-	-	-	0.5	1.0	-	-	-	2.5	-	-	-	-	-	10	-
	Farmland (Wet grain)	60	150$^{2)}$	≥0.5	5.0	-	1.0	-	0.5	-	-	-	0.5	1.0	-	-	-	2.5	-	-	-	-	-	5.0	-
	Farmland (Open-air vegetables)	40	100$^{2)}$	≥0.5	5.0	-	1.0	-	0.5	-	-	-	0.5	1.0	-	-	-	2.5	-	-	-	-	-	1.0	-
	Forestry	≤35$^{1)}$	≤90$^{2)}$		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Green space	≤10	-	-	≤0.5	-	-	-	≤0.5	-	-	-	-	≤1.0	-	-	-	≤2.5	-	-	≤8	-	-	-	-
AUS (EPHCA, 2006)	Landscape	<20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Commercial food crops	<20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Pasture or fodder crop	<20$^{1)}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Israel$^{12)}$ (WAI, 2010)	Unrestricted	10 <15	100 <150	>0.5	2	-	-	-	-	-	-	-	-	-	-	-	-	-	5 <15	25 <35	10 <15	-	-	-	-
Cyprus	All crops	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

CY. / ORG.	Classi-fication	Parameters (mg/L, except for markings)																							
		BOD_5	COD	DO	LAS	TPh	VPh	PCP	Chl-oral	PERC	TCS	TAI	Acrolein	FORMALD	TTHM	TAS	B(a)P	Benzene	TP	TN	NH_4^+	TO-NS	FOG	Petro.	Pesticides
(MANREC, 2005)	Vegetables eaten cooked	10 15$^{4)}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Crops for human consumption; Amenity areas of limited public access /Fodder crops	20 30$^{3)}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Industrial crops	50 70$^{4)}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
France (MSAPHF, 2014)	A	-	<60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Greece (MEECCG, 2011)	Restricted	≤25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Unrestricted	≤10$^{3)}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Urban uses and Periurban green	≤10$^{3)}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Italy (MHI, 2003)	Crops and green areas	20	100	-	0.5$^{5)}$	0.1	-	0.003	-	0.01	0.04	0.5	-	-	0.03	0.01	10^{-5}	10^{-3}	2	15	2	0.01	10	0.05$^{4)}$	0.05$^{6)}$ $10^{-4,7)}$ $10^{-5,8)}$
Jordan (ISMJ, 2006)	A	30	100	>2	100	<0.002$^{10)}$	-	-	-	-	-	-	-	-	-	-	-	-	-	45	30$^{9)}$	-	8	-	-
	B	200	500	-	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	70	45$^{9)}$	-	8	-	-
	C	300	500	-	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	100	70$^{9)}$	-	8	-	-
	Cut flowers	15	50	>2	15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	70	45$^{9)}$	-	2	-	-
Saudi Arabia (MOWE, 2000)	Unrestricted	10	-	-	-	0.002$^{10)}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.0 10.0$^{9)}$	-	-	-	-
	Restricted	40	-	-	-	0.002$^{10)}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.0 10.0$^{9)}$	-	-	-	-

Note: (1) Soluble BOD_5; (2) Indicates the chemical oxygen demand measured using potassium dichromate ($K_2Cr_2O_7$) as the oxidant, i.e. the potassium dichromate index COD_{Cr}; (3) 80% of samples; (4) Mineral oils; (5) Total surfactants; (6) Other pesticides; (7) Chlorinated biocides; (8) Phosphorated pesticides; (9) Nitrate Nitrogen (NO_3^-); (10) Phenol; (11) Methyl blue active substances (MBAS); (12) Regulations of Israel give maximum for arithmetic monthly average, maximum and minimum three kinds of restrictions, Table 3, Table 4 and Table 5 same as above. ***Source****: Author's own elaboration.*

For crops, the range of reasonable boron, B concentrations is very narrow. In arid, semi-arid or coastal areas, B often exceeds crop requirements due to poor drainage or intrusion of seawater with high B content and diffusion of seawater aerosols (Landi et al, 2019). Although B is involved in metabolic processes of many crops, some studies believe that the effect of B on vascular plants has been completely overturned (Lewis et al, 2019), so a new round of confirmation research and evaluation should be carried out on the toxicity of boron to crops. Therefore, it is necessary for many countries to specify B limits in their water quality standards for reclaimed water irrigation. At low concentrations, Selenium, Se has a positive effect on abiotic stress regulation (Kaur, 2014), but it is toxic to plants at concentrations more than 0.025mg/L.

Aluminum (Al) and Lithium (Li), are also metals that are easily accessible in daily life. The standard set by Israel is Al ≤5 mg/L and Li ≤2.5 mg/L

2.1.3 Heavy Metal Parameters

For different countries, there are a variety of heavy metal pollutant parameters, including Arsenic (As), Hydrargyrum (Mercury or Hg), Chromium (Cr), Nickel (Ni), Lead (Pb), Cadmium (Cd), Zinc (Zn), Iron (Fe), Copper (Cu), Manganese (Mn), Molybdenum (Mo), Vanadium (V), Beryllium (Be), Cobalt (Co), Barium (Ba), Stannum (Sn), Titanium (Ti), and Uranium (U). Heavy metals are widely used in agriculture, chemical industry, pharmaceutical industry and other fields, bringing certain risks to the environment and human health, and have always attracted people's attention (Tiwari et al, 2022). Therefore, it is necessary to control the content of heavy metal in reclaimed water. Heavy metals and their compounds are used in a wide variety of industries and are highly toxic, so they are distinguished from other inorganic and organic parameters and will be discussed separately in this section.

Heavy metal pollutants often have major impact on human health, such as As, Cr, and Cd, which can cause genomic instability, and high doses of Hg and lead Pb, which can induce severe complications such as kidney failure abdominal cramps, and bloody diarrhea (Balali-Mood et al., 2021; Bernhoft, 2012; Tsai et al., 2017). As, Co, Cr and Ni exhibit the highest toxicity in water bodies (Vinod et al., 2019). Although comprehensive parameters such as TDS and hardness will change if the heavy metal content is too high, it is still necessary to be concerned about the heavy metal items when it comes to more specific monitoring and tracing.

According to the list of carcinogens published by the WHO, Class I carcinogens include As, inorganic arsenic compounds, Be, beryllium compounds, Cd, cadmium compounds, chromium (Ⅵ) compounds, nickel compounds, et al. Class II carcinogens include Co, cobalt compounds, cobalt metal without tungsten carbide, cobalt sulfate and other soluble cobalt (II) salts, Pb, molybdenum trioxide, Ni and nickel alloys, et al. Class Ⅲ carcinogens include arsenobetaine and other organic arsenic compounds that are not metabolized in humans, chromium (Ⅲ) compounds, implanted foreign bodies of metallic chromium or titanium and of cobalt-based, chromium-based, and titanium-based alloys, stainless steel and depleted uranium, hematite, lead compounds (organic), maneb, Hg and mercury inorganic compounds., et al. Carcinogen categories can inform the selection of heavy metal pollutant indices, and in addition factors such as local industrial structure and geography are to be considered. For example, some studies have found that the content of Fe and Mn in surface water of China is relatively high. In the US, the average values of Mn, Co, As and Ni exceed the maximum allowable values for drinking water stipulated by the US EPA. And the average values of Ni, Cd and Cr in US surface water are also higher than the drinking water values recommended by WHO (2017) and USEPA (2009). Therefore, localities should reasonably select heavy metal parameters according to the survey and statistical results (Vinod et al, 2019).

It can be seen from the table that the limits of Cu, Mo and Co in China are 0.5-1.0 mg/L, 0.5 mg/L and 1.0 mg/L, respectively which are relatively less compared with that in other countries, especially for Mo and Co. Co at 0.1-1.0 mg/L is toxic to most crops. Feed crops grown from soils with high Mo content may be toxic to livestock. It is recommended to moderately lower the Mo and Co limits (Westcot and Ayers, 1985). The limit of Pb in the USA is also high compared to that of other countries. China’s restrictions on Be are too harsh. Jordan and Saudi Arabia have more lenient regulations for Zn at 5 mg/L and 4 mg/L respectively. Reclaimed water irrigation standards for heavy metal are often based on other types of water quality standards or Guidelines which are older. Most of the standards have references to criteria of FAO (Westcot and Ayers, 1985). Some of the limits in guidelines lack relevant data. For example, the limit value for Cr is stated as "Toxicological data are not available and conservative limits are recommended", and the limit value for Pb is stated as "Plant cell growth is inhibited at very high concentrations".

Table 2.2. Comparison of inorganic salt indexes of reclaimed water irrigation water quality in various countries

CY./ ORG.	Classi-fication	Parameters (mg/L, except for markings)																					
		TDS	Cl	Cl_2 res.	B	F	pH	SAR (mmol/L)	TWH	EC (dS/m)	Mg	Ca	Na	P	S	H_2S	SO_3	SO_4^{2-}	HCO_4^-	Se	Al	Li	CN
WHO (WHO, 2006)	Unrestricted /Restricted	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
USA (EPA, 2012)	Urban reuse (Un-restricted）	-	-	1(min.)	0.75	1.0	6.0-9.0	-	-	-	-	-	-	-	-	-	-	-	-	0.02	5.0	2.5	-
	Urban reuse (Restricted)	-	-	1(min.)	0.75	1.0	6.0-9.0	-	-	-	-	-	-	-	-	-	-	-	-	0.02	5.0	2.5	-
	Agri. Reuse (Food Crops）	-	-	1(min.)	0.75	1.0	6.0-9.0	-	-	-	-	-	-	-	-	-	-	-	-	0.02	5.0	2.5	-
	Agri. reuse (Processed Food Crops/Non-Food Crops)	-	-	1(min.)	0.75	1.0	6.0-9.0	-	-	-	-	-	-	-	-	-	-	-	-	0.02	5.0	2.5	-
Japan (MLIT, 2005)	Sprinkling water	-	-	0.1 4) ≥0.4 5)	-	-	5.8-8.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
China (AQSIQ, 2007, MWRC, 2007, AQSIQ, 2010, AQSIQ, 2020)	Farmland (Fibre crops)	1000 1) 2000 2)	350	1.5	1.0	2.0	5.5-8.5	-	≤450	-	-	-	-	-	1.0	-	-	-	-	0.02	-	-	0.5
	Farmland (Dry grain)	1000 1) 2000 2)	350	1.5	1.0	2.0	5.5-8.5	-	≤450	-	-	-	-	-	1.0	-	-	-	-	0.02	-	-	0.5
	Farmland (Wet grain)	1000 1) 2000 2)	350	1.0	1.0	2.0	5.5-8.5	-	≤450	-	-	-	-	-	1.0	-	-	-	-	0.02	-	-	0.5

	Farmland (Open-air vegetables)	1000	350	1.0	1.0	2.0	5.5-8.5	-	≤450	-	-	-	-	-	1.0	-	-	-	-	0.02	-	-	0.5
	Forestry	≤1000	-	-	-	-	5.5-8.5	-	≤450	-	-	-	-	-	-	-	-	-	-	-	-	-	≤0.05
	Green space	≤1000 2000[3]	≤250	≥1.0[6] 0.2-0.5[7]	≤1.0	≤2.0	6.0-9.0	≤9	≤500	-	-	-	-	-	-	-	-	<500	-	≤0.02	-	-	≤0.05
Israel (WAI, 2010)	Unrestricted	-	250 <280	1 0.8-2.5	0.4 <0.5	2 <3	6.5-8.5	5.0 <6.5	-	1.4 <1.8	-	-	150 <300	-	-	-	-	-	-	0.02 <0.05	5 <12.5	2.5 <6.25	0.1 <0.2
Italy (MHI, 2003)	Crops and green areas	-	250	0.2		1.5	6.0-9.5	10	-	3 <4	-	-	-	-	-	0.5	0.5	500	-	0.01	1	2.5	0.05
Spain (ASERSA, 2007)	Agri. uses	-	-	-	0.5	-	-	6.0	-	3.0	-	-	-	-	-	-	-	-	-	0.02	-	-	-
Jordan (ISMJ, 2006)	A/B/C	1500	400	-	1.0	2	-	9.0	-	-	100	230		30	-	-	-	500	400	0.05	5.0	0.075	0.1
	Cut flower	1500	400	-	1.0	2	-	9.0	-	-	100	230		30	-	-	-	500	400	0.05	5.0	0.075[8] 2.5	0.1
Saudi Arabia (MOWE, 2000)	Restricted	2500	-	0.5	0.75	1	-	-	-	-	-	-	-	-	-	-	-	-	-	0.02	5.0	2.5	-
	Unrestricted	2500	-	0.2-0.5	0.75	1	-	-	-	-	-	-	-	-	-	-	-	-	-	0.02	5.0	2.5	-

Note: (1) Non-Saline land; (2) Saline-alkali land; (3) The parameter values in brackets are parameters for areas with high TDS content in coastal and local water sources; (4) Free residual chlorine; (5) Combined residual chlorine; (6) Total chlorine residua (Leave the factory) (7) Total chlorine residua (End of pipe network); (8) or citrus. ***Source**: Author's own elaboration.*

Table 2.3. Comparison of heavy metal parameters of reclaimed water irrigation water quality in various countries

CY./ORG.	Classification	Parameters (mg/L, except for markings)																	
		As	**Hg**	**Cr**	**Ni**	**Pb**	**Cd**	**Zn**	**Fe**	**Cu**	**Mn**	**Mo**	**V**	**Be**	**Co**	**Ba**	**Sn**	**Ti**	**U**
USA (EPA, 2012)	Agricultural reuse	0.1	-	0.1	0.2	5.0	0.01	2.0	5.0	0.2	0.2	0.01	0.1	0.1	0.05	-	-	-	-
China (AQSIQ, 2007, MWRC, 2007, AQSIQ, 2010, AQSIQ, 2020)	Farmland (Fibre crops)	0.1	0.001	0.1[1)]	0.1	0.2	0.01	2.0	1.5	1.0	0.3	0.5	0.1	0.002	1.0	-	-	-	-
	Farmland (Dry grain)	0.1	0.001	0.1[1)]	0.1	0.2	0.01	2.0	1.5	1.0	0.3	0.5	0.1	0.002	1.0	-	-	-	-
	Farmland (Wet grain）	0.05	0.001	0.1[1)]	0.1	0.2	0.01	2.0	1.5	1.0	0.3	0.5	0.1	0.002	1.0	-	-	-	-
	Farmland (Open-air vegetables)	0.05	0.001	0.1[1)]	0.1	0.2	0.01	2.0	1.5	1.0	0.3	0.5	0.1	0.002	1.0	-	-	-	-
	Forestry	≤0.05	≤.001	≤0.1	-	≤0.10	≤0.01	-	-	-	-	-	-	-	-	-	-	-	-
	Green space	≤0.05	≤0.001	≤0.1[1)]	≤0.05	≤0.2	≤0.01	≤1.0	≤1.5	≤0.5	≤0.3	≤0.5	≤0.1	≤0.002	≤1.0	-	-	-	-
AUS (EPHCA, 2006)	Landscape/ Commercial food crops/ Nonfood crops/Pasture or fodder crop	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Israel (WAI, 2010)	Unrestricted(Monthly average)	0.1	0.002	0.1	0.2	0.1	0.01	2	2	0.2	0.2	0.01	0.1	0.1	0.05	-	-	-	-
	Unrestricted(Max.)	<0.25	<0.005	<0.25	<0.5	<0.25	<0.025	<5	<5	<0.5	<0.5	<0.025	<0.25	<0.25	<0.125	-	-	-	-
Italy (MHI, 2003)	Crops and green areas	0.02	0.001	0.1 0.005[1)]	0.2	0.1	0.005	0.5	2	1.0	0.2	-	0.1	0.1	0.05	10	3	0.001	-
Spain (ASERSA, 2007)	Agri. uses	0.1	-	0.1	0.2	-	0.01	-	-	0.2	0.2	0.01	0.1	0.1	0.05	-	-	-	-
Jordan (ISMJ, 2006)	A/B/C/Cut flower	0.1	0.002	0.1	0.2	0.2	0.01	5.0	5.0	0.2	0.2	0.01	0.1	0.1	0.05	-	-	-	-
Saudi Arabia (MOWE, 2000)	Restricted	0.1	0.001	0.1	0.2	0.1	0.01	4.0	5.0	0.4	0.2	0.01	0.1	0.01	0.05	-	-	-	-
	Unrestricted	0.1	0.001	0.1	0.2	0.1	0.01	4.0	5.0	0.4	0.2	0.01	0.1	0.1	0.05	-	-	-	-

Note： Represents hexavalent Chromium. ***Source****: Author's own elaboration.*

2.1.4 Hygiene and Sensory Parameters

Hygiene and sensory parameters are the top priority of reclaimed water quality requirements, and WHO and other organizations or countries have requirements for E. coli and worm egg indicators, but there are no clear requirements for other types of indicators.

The hygiene and sensory parameters mainly include *Escherichia coliform* (*E. coli*), *fecal coliform*, *salmonellae*, *legionella spp.*, Ascaris Lumbricoides eggs, Taenia saginata and Taenia solium eggs, Helminth Eggs, Chromaticity, Turbidity, Stink, Total Suspended Solids (TSS), and Exterior.

E. coli, *fecal coliforms*, ascaris lumbricoides eggs, and helminth eggs are pathogenic biological parameters. Common parameter bacteria include total coliforms, *fecal coliforms* and *E. coli*. Total coliform is a group of bacteria with certain characteristics related to fecal contamination, and *fecal coliform*, which is part of total coliform, can reflect the degree of fecal contamination of water more precisely than total coliform *E. coli* is the main species of total coliforms and *fecal coliforms*. *Salmonella* is a pathogenic bacterium excreted in feces by human and animal patients or carriers (SEPA, 2002; Chen and Yang, 2020), which appears in water with great variability and the isolation technique has limitations in sensitivity and selectivity. Currently, *E. coli* is more accurate in indicating fecal contamination, which can be used as parameter bacteria in many countries around the world (Tallon, 2005, SEPA, 2002; Khan et al, 2019; AQSIQ, 2020), and the definitions of total coliform and *fecal coliform* often need to be changed with taxonomic updates, many of which are not related to fecal contamination, especially total coliform.

In Table 2.4, the survival rates of pathogens in soil vary from a few hours to several years (Pettygrove and Asano, 1985.), which depend on several factors, including soil moisture, temperature, pH, sunlight, organic matter content, etc. Coliforms have survival rate of 38 days. Fecal streptococci remain viable for 26 to 77 days. *Brucella* abortus is reported to be viable for 30 to 125 days.

Table 2.4. Survival of pathogens in soils

Organism	Survival time (days)
Coliforms	38
Streptococci	35 to 63
Fecal streptococci	26 to 77
Salmonellae	15 to > 280
Salmonella typhi	1 to 120
Tubercle bacilli	> 180
Leptospira	15 to 43
Entamoeba histolytica cysts	6 to 8
Enteroviruses	8 to 175
Ascaris ova	Up to 7 years
Hookworm larvae	42
Brucella abortus	30 to 125
Q-fever organisms	148

Source:

- *Gerba, C. P., Wallis, C., Melinick, J. L., 1975. Fate of wastewater bacteria and viruses in soil. ASAE Irrig. Drainage Div. J. IR3:157-174.*
- *Parsons, D., Brownlee, C., Wetler, D., Maurer, A., Haughtton, E., Kornder, L., Selzak, M., 1975. Health aspects of sewage effluent irrigation. Pollt. Control Branch, British Columbia, Water Resources Service Dept. Of land, Forests, and Water Resources, Victoria B.C.*
- *Burge, W.D., Marsh, P.B., 1978. Infectious Disease Hazards of Landspreading Sewage Wastes. J. Environ. Qual., 7:1-9.*

Table 2.5. Comparison of hygiene and sensory parameters of reclaimed water irrigation water quality in various countries

CY./ ORG.	Classification	Parameters (mg/L, except for markings)											
		E.coli **(CUF/100 ml)**	***Fecal Coliform*** **(CUF/100 ml)**	***Salmonellae*** **(CUF/100 ml)**	***Legionella spp.*** **(CUF/L)**	**Ascaris Lumbricoides eggs /L**	**Taenia saginata and Taenia solium eggs /L**	**Helminth eggs /L**	**Chro-mati-city**	**Turbidity (NTU)**	**Stink**	**TSS**	**Exterior**
WHO (WHO, 2006)	Unrestricted	≤1000 $<10^{4}$[1)]	-	-	-	-	-	≤1	-	-	-	-	-
	Restricted	$\leq 10^{5}$ $<10^{6}$[2)]	-	-	-	-	-	≤1	-	-	-	-	-
EU (EP&CEU, 2020)	A	≤10	-	-	≤1000	-	-	-	-	≤5	-	≤10	-
	B	≤100	-	-	≤1000	-	-	≤1[3)]	-	-	-	≤35	-
	C	≤1000	-	-	≤1000	-	-	≤1[3)]	-	-	-	≤35	-
	D	$\leq 10^{4}$	-	-	≤1000	-	-	-	-	-	-	≤35	-
USA (EPA, 2012)	Urban reuse (Unrestricted)	-	No detectable (median)	-	-	-	-	-	-	≤2	-	-	-
	Urban reuse (Restricted)	-	≤200 (median)	-	-	-	-	-	-	-	-	≤30	-
	Agri. Reuse (Food Crops)	-	No detectable (median)	-	-	-	-	-	-	≤2	-	-	-
	Agri. reuse (Processed food crops /non-food crops)	-	≤200 (median)	-	-	-	-	-	-	-	-	≤30	-
Japan (MLIT, 2005)	Sprinkling water	No detectable (1000)	-	-	-	-	-	-	-	≤2	No unpleasant sensation	-	No unpleasant sensation
China (AQSIQ, 2007, MWRC, 2007, AQSIQ, 2010, AQSIQ, 2020)	Farmland (Fibre crops)	-	≤4000	-	-	≤2	-	-	≤30	≤10	-	≤100[7)]	-
	Farmland (Dry grain)	-	≤4000	-	-	≤2	-	-	≤30	≤10	-	≤90[7)]	-
	Farmland (Wet grain)	-	≤4000	-	-	≤2	-	-	≤30	≤10	-	≤80[7)]	-
	Farmland (Open-air vegetables)	-	≤2000	-	-	≤2	-	-	≤30	≤10	-	≤60[7)]	-
	Forestry	-	≤1000	-	-	-	-	-	≤30	≤10	-	≤30[7)]	-
	Green space (Restricted)	No detectable	≤20 (median)	-	-	≤2	-	-	≤30	≤10	No unpleasant sensation	-	-
	Green space	No detectable	≤100 (median)	-	-	≤1	-	-	≤30	≤5	No unpleasant	-	-

	(Unrestricted)										sensation		
AUS (EPHCA, 2006)	Landscape irrigation	<1000(if not disinfected)	-	-	-	-	-	-	-	-	-	$<30^{7)}$	-
	Commercial food crops consumed raw or unprocessed	<1	-	-	-	-	-	-	-	-	-	-	-
	Commercial food crops	<1000	-	-	-	-	-	-	-	-	-	$<30^{7)}$	-
	Nonfood crops	<10000	-	-	-	-	-	-	-	-	-	-	-
	Pasture or fodder crop (limited withholding period)	<100	-	-	-	-	-	-	-	-	-	$<30^{7)}$	-
	Pasture or fodder crop (withholding period)	<1000	-	-	-	-	-	-	-	-	-	$<30^{7)}$	-
Russia (MHR, 1996)	Wastewater Irrig.	<1000	-	-	-	<1	-	<1	-	-	-	-	-
Israel (WAI, 2010)	Unrestricted	-	10 <50	-	-	-	-	-	-	-	-	10 <15	-
Cyprus (MANREC , 2005)	All crops	-	$\le 15^{10)}$ $5^{8)10)}$	-	-	-	-	None	-	-	-	$10^{7)8)}$	-
	Vegetables eaten cooked	-	$\le 10^{10)}$ $50^{8)10)}$	-	-	-	-	None	-	-	-	$\le 15^{7)}$ $10^{7)8)}$	-
	Crops for human Consumption; Amenity areas of limited public access	-	$\le 1000^{10)}$ $200^{8)10)}$	-	-	-	-	None	-	-	-	$\le 45^{7)}$ $30^{7)8)}$	-
	Fodder crops	-	$\le 5000^{10)}$ $1000^{8)10)}$	-	-	-	-	None	-	-	-	$\le 45^{7)}$ $30^{7)8)}$	-
	Industrial crops	-	$\le 10^{4,10)}$ $3000^{8)10)}$	-	-	-	-	-	-	-	-	-	-
France (MSAPHF, 2014)	A	≤250	-	-	-	-	-	-	-	-	-	≤15	-
	B	$\le 10^4$	-	-	-	-	-	-	-	-	-	-	-
	C	$\le 10^5$	-	-	-	-	-	-	-	-	-	-	-
	D	-	-	-	-	-	-	-	-	-	-	-	-
Greece (MEECCG , 2011)	Restricted	≤200	-	-	-	-	-	-	-	-	-	35	-
	Unrestricted	$\le 5^{8)}$ $\le 50^{9)}$	-	-	-	-	-	-	-	-	-	$\le 2^{8)}$	-

	Urban uses and Periurban green	-	≤2$^{8)}$ ≤20$^{9)}$	-	-	-	-	-	-	-	-	≤2$^{8)}$	-
Italy (MHI, 2003)	Crops and green areas	≤100 10$^{8)}$	-	absent	-	-	-	-	-	-	-	-	-
Portugal (IQP, 2005)	A	-	≤100$^{11)}$	-	-	-	-	≤1	-	-	-	-	-
	B	-	≤200$^{11)}$	-	-	-	-	≤1	-	-	-	-	-
	C	-	≤1000$^{11)}$	-	-	-	-	≤1	-	-	-	-	-
	D	-	≤10$^{4,11)}$	-	-	-	-	≤1	-	-	-	-	-
Spain (ASERSA, 2007)	Urban uses (Q1)	0	-	-	100$^{13)}$	-	-	0.1$^{6)}$	-	2	-	10$^{7)}$	-
	Urban uses(Q2)	200	-	-	100$^{13)}$	-	-	0.1$^{6)}$	-	10	-	20$^{7)}$	-
	Agri. uses(Q1)	100	-	c=3$^{12)}$ M=1000$^{12)}$	1000$^{13)}$	-	-	0.1$^{6)}$	-	No set limit	-	35$^{7)}$	-
	Agri. uses(Q2)	1000	-	c=3$^{12)}$ M=1000$^{12)}$	-	-	1$^{14)}$	0.1$^{6)}$	-	No set limit	-	35$^{7)}$	-
	Agri. uses(Q3)	10^4	-	-	100$^{13)}$	-	-	0.1$^{6)}$	-	No set limit	-	35$^{7)}$	-
Jordan (ISMJ, 2006)	A	100$^{10)}$	-	-	-	-	-	≤1	-	10	-	50	-
	B	1000$^{10)}$	-	-	-	-	-	≤1	-	-	-	200	-
	C	-	-	-	-	-	-	≤1	-	-	-	300	-
	Cut flowers	<1.1$^{10)}$	-	-	-	-	-	≤1	-	5	-	15	-
Saudi Arabia (MOWE, 2000)	Urban use (Unrestricted)	2.2$^{10)}$	-	-	-	-	-	1	-	-	-	10	-
	Urban use (Restricted)	1000$^{10)}$	-	-	-	-	-	-	-	-	-	40	-
	Agri. uses (Unrestricted)	2.2$^{10)}$	-	-	-	-	-	1	-	-	-	10	-
	Agri. uses (Restricted)	1000$^{10)}$	-	-	-	-	-	1	-	-	-	40	-

Note: (1) High-growing leaf crops or drip irrigation; (2) When exposure is limited or regrowth is likely; (3) For irrigation of pastures or forage; (4) Single sample; (5) 2 consecutive samples; (6) At least the following genera must be included in all quality categories: Ancylostoma, Trichuris and Ascaris; (7) Suspended solids (SS); (8) 80% samples; (9) 95% samples; (10) MPN/100 ml; (11) NMP/100 ml or CFU/100 ml; (12) Where n = number of aliquot samples analyzed; m = (MAV) maximum acceptable value for the bacterial count; M = maximum permitted value for the bacterial count (MAV + Maximum Deviation Limit); c = maximum number of aliquot samples whose bacterial count falls between "m" and "M"; (13) If there is a risk of aerosolization; (14) When irrigating pasture land for milk- or meat producing animals; (15) If irrigation wate. ***Source****: Author's own elaboration.*

The migration of the typical bacteria in unsaturated soil is related to health risk. Information on movement of bacterial through soils in relation to wastewater application has been summered in Table 2.6. Fecal streptococci travel to maximum distance of 183 m in silty sand and gravel. Bacillus stearothermophilus travels to 28.7 m in Crystalline bedrock within 30 hours.

Table 2.6. Movement of bacteria through soils in relation to wastewater application

Nature of fluid	Organisms	Media	Maximum distance traveled (m)	Time of travel
Tertiary treated wastewater	Coliform	Fine to medium sand	6.1	--
Secondary sewage effluent on percolation beds	Fecal coliforms	Fine loamy sand to gravel	9.1	--
Primary sewage in infiltration beds	Fecal streptococci	Silty sand and gravel	183	--
Inoculated water and diluted sewage injected subsurface	Bacillus stearothermophilis	Crystalline bedrock	28.7	24-30 hr
Sewage in buried latrine intersecting groundwater	Bacillus coli	Sand and sandy clay	10.7	8 weeks
Canal water in infiltration basins	Escherichia coli	Sand dunes	3.1	--

Source:

- *Gerba, C. P., Wallis, C., Melinick, J. L., 1975. Fate of wastewater bacteria and viruses in soil. ASAE Irrig. Drainage Div. J. IR3:157-174.*
- *Hagedorn, C., McCoy, E.L., Rahe, T.M., 1981. The potential for groundwater contamination from septic effluents. J. Environ. Qual., 10:1-8.*

For a given volume of water applied, an increase in application rate for drip irrigation results in an increase in the wetted radius and a decrease in the wetted depth. In the sandy loam soil, the water spreads out in a circular-arc shaped saturated zone on the surface, and the ultimate saturated entry radius increases as the application rate rises. An increasing application rate of water allows a more rapid transport of bacteria, thus accelerating *E. coli* transport rate and resulting in a larger distributed volume of *E. coli* for both soil types. For the sandy soil, more than 70% of the *E. coli* that is detected within the entire wetted volume concentrate in the range of 10 cm from the point source, and the concentration of *E. coli* decreases greatly as the distance from the point source increases. More than 98% of the *E. coli* is detected in a range of 5 cm around the saturated wetted zone for the sandy loam soil. To reduce bacterial concentration in the sewage effluent during wastewater treatment is important to decrease the risk of soil contamination caused by irrigation with sewage effluent.

The transport and fate of bacteria in unsaturated soil could be depicted using a modified form of the convection–dispersion equation that incorporates adsorption into two types of kinetics (e.g. HYDRUS-2D/3D model). The simulated results confirmed the observations in the laboratory experiment. The *E. coli* concentration is relatively high near the point source and decreases considerably with distance from the point source in both soil types. Nevertheless, *E. coli* is transported further in the sandy soil than in the sandy loam soil. In addition, an increasing application rate of water suspends bacteria, accelerates water flux, and enhances the *E. coli* transport rate, resulting in a larger distributed area with a higher *E. coli* concentration in both soil types. In the proximity of the point source, an extremely high concentration of *E. coli* is found under both simulated and observed conditions.

The transport of *E. coli* in soil and its residuals on plant leaves are controlled by many variables of drip irrigation, including lateral depth, irrigation level, irrigation frequency, *E. coli* contained in sewage effluent as well as environments.

The initial and final *E. coli* concentrations detected in soil were considerably low with a maximum value of about 2 CFU/g in the field experiments. The drip irrigation with secondary sewage effluent did not lead to obvious accumulation of *E. coli* in soil. The colonies of *E. coli* were most likely found in the top 0–20 cm layer of soil of the surface drip irrigation treatments. *E. coli* was hardly detected in all treatments at 72 h after irrigation for all irrigation events. It might be recommended that irrigation with sewage effluent should be prohibited within three days prior to harvest to avoid pathogen contamination to crop products. A higher irrigation frequency increased short term *E. coli* contamination of soil as it increased contacting opportunities between sewage effluent and soil. A less frequent irrigation with intervals of more than three days was therefore recommended to reduce the contamination risk of *E. coli*. No *E. coli* uptake was detected within the stems of asparagus lettuce. Few counts of *E. coli* were detected on the leaves of the crop but a weak association between the irrigation management practices and *E. coli* contamination of leaves was found, suggesting a low risk of *E. coli* contamination resulted from drip irrigation with sewage effluent. Subsurface drip irrigation (SDI) has advantage in reducing pathogen contamination to soil and crop plants over surface drip irrigation and is therefore a promising selection in avoiding pathogen contamination when applying sewage effluent.

As a porous media, soil can function as both a filter and a passage for pathogen. When applying sewage effluent, the pathogens may pollute groundwater through either preferential flow or leached solution. The results of a two year of field experiments indicate that similar population and presence of *E. coli* in soil were detected before and after the application of reclaimed water while about 80% of *E. coli* were detected in 0-20 cm depths. No *E. coli* was detected in leached solutions resulted from an irrigation or a rainfall during both entire study periods. No *E. coli* detected in the leachate under unsaturated conditions may be mainly due to either the *E. coli* was retained in the soil matrix or died off before leaching. The soil could effectively filter *E. coli* to avoid groundwater contamination, especially under unsaturated condition. Using subsurface drip irrigation to apply sewage effluent did not lead to *E. coli* leaching in a medium textural soil of silt loam.

The movement of viruses through various systems is summarized in Table 2.7. The removal efficiencies vary from 50% to 100%, and the distances of travel range from several centimeter to 60 m. The mobility of viruses is related to the cation exchange, pH, hydraulic soil conductivity, surface area, organic matter content, soil texture and the flow rate of percolating fluid (Pettygrove & Asano, 1985).

Table 2.7. Movement of viruses through soil

Virus type	Nature of fluid	Nature of medium	F1ow rate	Distance of trave1	Percentage of removal
T1, T2, f2	Distilled water with added salts	9 types of soils from California	0.078 to 0.313 mL/min	45 to 50 cm	>99
Poliovirus I	Disti1led water	Dune sand	I to 2 mL/min	2o cm	99.8 to 99.9
Poliovirus 2	Distilled water	Low humic laterso1s	100 to 140 gal/day·ft^2	1.5 to 6 inch	96 to 99.3
Poliovirus 2	Secondary effluent	Sandy grave1	--	60m	100
Coxsackie	Spring water	Garden soils	--	36 inch	50
T4	Distil1ed water	Low humic latersols	100 to 140 ga1/day·ft^2	1.5 to 6 inch	100
T7	Secondary treated	Sandy forest	--	19.5 cm	99.6
Indigenous enteric viruses	Secondary effluent	Loamy sand soil	Intermittent avg:0.02 cm/min	3 to 9 m	100

Source:

- *Gerba, C. P., Wallis, C., Melinick, J. L., 1975. Fate of wastewater bacteria and viruses in soil. ASAE Irrig. Drainage Div. J. IR3:157-174.*
- *Bitton, G., 1975. Adsorption of viruses onto surface on activated carbon. Am. Water Works Assoc. J., 61:52-56.*
- *Vilker, V.L., 1981. Simulating virus movement in soils. p. 223-253. In: Iskandar, I. K., Modeling wastewater renovation land tratment. Wiley and Sons, New York.*

2.2 Suggested water quality requirements

According to the above comparative analysis, it is obvious that different countries or organizations set up different water quality Guidelines. It is most important to control environmental risks and health risks in reclaimed water irrigation. The three parameters of BOD, pH and B are selected as basic parameters for environmental risk control. The three parameters of Chlorine residual, TSS and *E. coli* are selected as basic parameters for health risk control, and *E. coli* is the indicator parameter required by WHO. As shown in table 2.8, basic control parameters of suggested water quality requirements for reclaimed water irrigation are proposed for different plant classes.

Table 2.8. Suggested basic control parameters of water quality requirements for reclaimed water irrigation

Parameters	Quality requirements*		
	A	B	C
BOD (mg/L)	≤10	≤30	≤80
pH (dimensionless)	6.0-9.0	6.0-9.0	6.0-9.0
Chlorine residual (mg/L)	≥1.5	≥1.0	≥0.4
TSS (mg/L)	≤30	≤60	≤90
B (mg/L)	≤0.75	≤0.75	≤0.75
E. coli (CUF /100 ml)	≤10	≤1000	≤10^4

Note: A: All food crops consumed raw or unprocessed.
B: Processed food crops, fodder crop; public parks and gardens, sport lawns, forest with public easy access.
C: Nonfood crops; sod farms, forest and lawns rarely accessed by the public or located in places of difficult or controlled public access.
Source*: Author's own elaboration based on summary of various research results and documents.*

As shown in Table 2.9, the organic parameters of SAR and EC are selected to control soil salinization (WHO, 2006, EPA, 2012, MLIT, 2005, AQSIQ, 2002, MWRC, 2007, AQSIQ, 2007, AQSIQ, 2010, AQSIQ, 2020, EPB,2015a, EPB, 2015b, EPHCA, 2006, Inbar Y., 2010). Heavy metal parameters of As, Hg, Cr, Ni, Pb, Cd, Zn, Fe, Cu, Mn, Mo, V, Be, Co are retained to control soil environmental pollution. Nineteen parameters are kept as selective control parameters of water quality requirements for reclaimed water irrigation. The monitoring frequencies of selective control parameters should be lower than those of basic control parameters.

Table 2.9. Suggested selective control parameters of water quality requirements for reclaimed water irrigation

Parameters	A	B	C
SAR (mmol/l)	≤10	≤10	≤10
EC (dS/m)	≤0.7	≤0.7	≤0.7
As (mg/L)	≤0.1	≤0.1	≤0.1
Hg (mg/L)	≤0.001	≤0.001	≤0.001
Cr (mg/L)	≤0.1	≤0.1	≤0.1
Ni (mg/L)	≤0.2	≤0.2	≤0.2
Pb (mg/L)	≤0.2	≤0.2	≤0.2
Cd (mg/L)	≤0.01	≤0.01	≤0.01
Zn (mg/L)	≤2.0	≤2.0	≤2.0
Fe (mg/L)	≤2.0	≤2.0	≤2.0
Cu (mg/L)	≤0.2	≤0.2	≤0.2
Mn (mg/L)	≤0.3	≤0.3	≤0.3
Mo (mg/L)	≤0.01	≤0.01	≤0.01
V (mg/L)	≤0.1	≤0.1	≤0.1
Be (mg/L)	≤0.1	≤0.1	≤0.1
Co (mg/L)	≤0.05	≤0.05	≤0.05
Li (mg/L)	≤2.5	≤2.5	≤2.5
Al (mg/L)	≤5.0	≤5.0	≤5.0
Se(mg/L)	≤0.02	≤0.02	≤0.02

Source*: Author's own elaboration based on summary of various research results and documents.*

2.3 Single parameter evaluation

Quality data of reclaimed water, soil, plant, and groundwater are collected or monitored to calculate pollution indexes (P_i) as the following Eq. 2.1.

$$P_i = \frac{C_i}{C_{oi}} \quad (2.1)$$

Where P_i is the pollution index of the i_{th} evaluation parameter; C_i is the value of the i_{th} evaluation parameter; C_{oi} is the standard limit value of the i_{th} evaluation parameter.

We can assess the pollution degree with the value of pollution index, the higher the value, the larger the evaluation parameter. It indicates that the substance is not polluted If P_i is smaller than 1, the substance is not polluted; if it is larger than 1, the substance is polluted.

* * *

3. Crop Classification and Selection

3.1 Crop Selection based on health risk control

3.1.1 Occurrence and harm of emerging contaminants

Emerging contaminants (ECs) are those synthetic or naturally occurring compounds which are not commonly monitored in the environment, but have the potential to enter the environment and cause known or suspected adverse ecological and/or human health effects. ECs are widely derived from human production and living processes, and are discharged into urban and municipal pipe networks along with industrial, agricultural and domestic sewage, resulting in a large number of residual pollutants flooding into the water environment and various other environmental media (Liu et al., 2017; Sunyer-Caldú et al., 2022). ECs can refer to many different kinds of chemicals, including pharmaceuticals and personal care products (PPCPs), endocrine disrupting chemicals (EDCs), perfluorochemicals (PFCs), brominated flame retardants (BFRs), antibiotics, antibiotic resistance genes (ARGs), phthalates esters (PAEs) and microplastics (MPs), among others. These frequently detected chemicals in aquatic environment are becoming one of the major challenges to the environment and human health.

Reclaimed water is a major source of dissemination of ECs in environment. ECs in wastewater treatment plants (WWTP) have been investigated in many countries and regions. In the research of Huang er al. (2018), 5 pharmaceuticals—nifedipine (NIP), atenolol (ATE), metoprolol (MET), valsartan (VAL) and pravastatin (PRA)—were detected in the final effluents from three WWTPs in south China, of which the average concentrations were in the range of ND-20.5, ND-6.73, 97.6-613.2, 8.4-171.3 and 28.9-74.2 ng/L, respectively. The concentration level of EDCs in aquatic environment is ng/L-μg/L (Bruin et al., 2019). Lin er al. (2020) reported that 7 EDCs including estrone (E1), estradiol (E2), estriol (E3), and 17α-ethynylestradiol (EE2) and bisphenol A (BPA) were detected in a WWTP effluent in Ningbo, China with the mean concentrations in the range of 7-56 ng/L. Perlfuorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS), listed in the Stockholm Convention in 2009 and 2019 respectively, are the two most typical types of PFCs in the environment. PFOA and PFOS were found dominant among the 14 perfluoroalkyl acids in the surface water of Huangpu River, Shanghai, China with mean concentrations of 139.6 and 46.5 ng/L, respectively (Sun et al., 2017), which were below the threshold for drinking water, 200 ng/L for PFOA and 400 ng/L for PFOS, set by USEPA (2009). Four novel BFRs, i.e., decabromodiphenylethane (DBDPE), 1,2-bis(2,4,6-tribromophenoxy) ethane (BTBPE), pentabromoethylbenzene (PBEB), and hexabromobenzene (HBB) were studied in liquid samples collected from 20 Canadian wastewater treatment plants and were identified with the median concentration level of effluents at 200, 120, 6.6 and 0.94 pg/L, respectively (Kim et al., 2014). In Wang et al.'s (2021) report, the total concentrations of the ten antibiotics (ofloxacin, norfloxacin, ciprofloxacin, roxithromycin, azithromycin, erythromycin, tetracycline, oxytetracycline, chlortetracycline, and sulfamethoxazole) in the secondary effluents were 1441.6-4917.6 ng/L with ofloxacin having the highest concentration, and the absolute and relative abundances of total ARGs in the secondary effluents were 10^3-10^4 copies/mL. The four reclaimed water treatment plants (RWTPs) investigated removed 43.5-98.9% of antibiotics and 0.19-2.91 log of ARGs (Wang et al., 2021). Phthalates esters (PAEs) and microplastics (MPs) are two typical plastic-waste-related pollutants that inevitably enter the water environment (Lee et al., 2018). The total concentrations of PAEs were detected between 568.9 to 1847.5 ng/L in effluents from the four wastewater treatment plants in three northern cities of China and MPs were detected in the range of 276–1030 items/L (Wang et al., 2021).

Although the potential ecological and human health risks of ECs have been discussed in recent decades, our understanding of ECs is still rather limited. Given a large number of ECs and their occurrence at trace levels, it is urgent to develop strategies to prioritize ECs, which will benefit the future reuse of reclaimed water in agriculture.

3.1.2 Translocation and accumulation of ECs in soil-plant system

3.1.2.1 General characteristics

Translocation of ECs to roots, stems, leaves and fruits under reclaimed water irrigation was affected by its concentration, soil physical and chemical properties, rhizosphere microorganisms and enzyme activities in plants (John et al., 2000; Dodgen et al., 2013). Lipid content in roots will affect the absorption of hydrophobic organics by plants (Simonich and Hites, 1995). Hydrophobic organics with $\log_{kow}$ between 1-3.5 have high mobility (Pilon Smits, 2005). For the distribution characteristics, the highest content was in roots of plants, such as wheat, corn, rice, soybean, sorghum, vegetables and others. The content in stem, leaf and seed is much lower than that in root (Mortensen and Kure, 2003; Imadeddin et al., 2004; Lu et al., 2015). Accumulation coefficient in plant varies with pollutant concentration in soil. Compared with stem and leaf tissues, the accumulation coefficient of root is the largest. The accumulation coefficients are 0.60-5.80 and 0.063-1.45, respectively for NP and BPA in wheat root. The accumulation coefficients of leaf vegetables were higher than those of fruit vegetables (Dodgen et al., 2013; Yang et al., 2014; Wang et al., 2018). The absorption capacity of wheat and vegetables to NP is greater than BPA (Lu et al, 2015). Chi et al. (2018) proved by soil culture experiment that Chinese cabbage and lettuce could absorb antibiotic, such as oxytetracycline, tetracycline and chlortetracycline. As to their accumulation and transport ability, Chinese cabbage outperforms lettuce, and the underground part beats the upper part.

The absorption of ECs in plant roots is related to the ion trap of cell wall and electrostatic interaction (Miller et al., 2016). After being absorbed by root system, ECs enter the upper part of the plant through the xylem with transpiration, and most of them are accumulated in cell fluid and symplast (Goldstein et al., 2014). The mobility and accumulation are related to ECs' lipophilicity. Highly lipophilic compounds are easily absorbed by intracellular fat and their mobility is reduced. For instance, antibiotics, such as tetracycline, are more easily transported and accumulated by plants because of high water-solubility (Wu et al., 2015). After absorbing ECs, ECs migrate to the ground part through transpiration flow. Therefore, transpiration factor is used to characterize the migration capacity of organic pollutants from root to upper ground (Lin et al., 2013).

In plants, ECs can undergo biological metabolism to varying degrees, or be "locked" in cell fluid or cells. In the wall, its migration behavior is inhibited (Burken, 2003), so as to reduce the accumulation in the crop fruit, and finally reduce the risk of human exposure. The absorption of ECs by plants will affect plant germination and seedling growth. For instance, low concentration of BPA (1.0-5.0 mg/L) will promote root growth and increase fresh weight. High concentration of BPA (10.0-50.0 mg/L) will inhibit crop growth (Pan et al., 2013; Qiu et al., 2013). When the concentration of NP in soil reaches 10g/kg, it will have a significant negative impact on soil respiration and plant enrichment (Roberts et al, 2006).

Uptake of organic compounds by plants and mobility to groundwater are found to be influenced by physico-chemical features of the compounds, environmental conditions and the characteristics in Table 3.1 and 3.2 (Durate-Davidson and Jones, 1996; Harms, 1996; Polder et al, 1995).The bioconcentration factor (BCF) is the ratio of the concentration of contaminants in plants and in soils. It is an indicator of a plant's capacity to accumulate pollutants. Translocation factor (TF) is the ratio of the above ground element content to the underground element content. The BCF and TF are used to express the uptake of a contaminant by plants from soil and the transportation to aerial parts from the roots. Reports show that wheat, corn, rice, soybean and vegetables differ significantly in their capacity of accumulating or transporting contaminants. There are various ECs in reclaimed water and soil; the pollution is long-term, concealed, and irreversible. The cumulative risk of irrigation has attracted widespread concern.

Table 3.1. The potential for organic compounds being adsorbed onto the root surface of plants and leaching into groundwater

Classification	K_{ow}*	Potential for root retention	Mobility in soil
Class 1	$\log K_{ow} > 4.0$	High	Low
Class 2	$2.5 < \log K_{ow} < 4.0$	Medium	Medium
Class 3	$\log K_{ow} < 2.5$	Low	High

* K_{ow}, Octanol-water partition coefficient of an organic compound; ***Source****: Polder, M. D., Hulzebos, E. M., Jager, D. T., 1995. Validation of models on uptake of organic chemicals by plant roots. Environmental Toxicology and Chemistry, 14: 1615-1623.*

Table 3.2. The potential for plant root uptake and translocation

Classification	K_{ow}^{A}	Potential for root retention	Potential for uptake and translocation
Class 1	$1.0 < \text{Log } K_{ow} < 2.5$	High	Low
Class 2	$2.5 < \text{Log } K_{ow} < 3.0$ or $0.5 < \text{Log } K_{ow} < 1.0$	Medium	Medium
Class 3	$\text{Log } K_{ow} < 0.5$ or $\text{Log } K_{ow} > 1.0$	Low	High

***Source**: Durate-Davidson and Jones, 1996. Screening the environmental fate of organic contaminants in sewage sludges applied to agricultural soils: 1. The potential for transfer to plants and grazing animals. Science of the Total Environment, 185:59-70.*

3.1.2.2 The accumulation and transportation of EDCs in soil-crop system

Endocrine disrupting chemicals (EDCs) are typical types of ECs widely found in reclaimed water. NP and BPA are two typical EDCs. The concentration of NP was found to range from 2.92 to 15 μg/L in sewage effluents (Sun et al., 2010) and 79.6-1017.2 μg/kg in soil of 30-year-old sewage irrigation areas (Liao, 2013). The concentrations of BPA in soils and reclaimed water are 0.55-147 μg/kg and 0.15-2 μg/L, respectively (Campbell et al., 2006; Gibson et al., 2010; Sidhu et al., 2015; Diao et al., 2017).

In order to study the accumulation of EDCs in soil-plant system, Wang et al (2018) and Hu et al. (2021) studied NP and BPA in their research. They irrigated soil with simulated reclaimed water of different concentrations of NP and BPA. Meanwhile, winter wheat and celery were selected as the commonly used crops in North China. According to the research data, the BCFs of NP and BPA in roots, stems, leaves, and grains of the winter wheat all decreased with their added concentrations in soils. The average BCFs of NP and BPA in winter wheat showed negative exponential relations to their concentrations in soil. For celery, both the BCFs and TF of NP decreased with the initial NP concentrations in soil. The accumulation equations for NP and BPA in plants are listed in Table 3.3.

Table 3.3. Accumulation equations and BCF, TF of EDCs in plants

EDCs	Plants	Equation ($BCF=y_0+ae^{-bCs}$)	BCFs	TF
NP	winter wheat	$BCF=0.088+5.10e^{-1.38Cs}$ ($R^2=0.96$)	0.088–2.765	-
	celery	$BCF=6.65\times10^{-4}+0.02e^{-0.016Cs}$ ($R^2=0.934$)	0.38–4.86	0.30-1.55(stems-roots), 0.42-2.17(leaves-roots), 0.38-1.92(aerial parts- roots)
BPA	winter wheat	$BCF=0.022+2.39e^{-11.2Cs}$ ($R^2=0.99$)	0.022–0.743	-

***Source**: Author's own elaboration.*

According to the mass balance calculation, the results showed a limited NP and BPA enrichment capacity of plants and low residual rates in soil-plant system. The amounts of NP and BPA in soil-winter wheat system accounted for 8.99-28.24% and 2.35-4.95%, respectively, of the initial amounts added into the soils (Wang et al., 2018). The residual rates of NP in soil-celery system were between 6.33% and 26.3% (Hu et al., 2021). These results suggest that the residual organic pollutants in soil and the uptake of organic pollutants by plants are very limited.

3.1.2.3 The accumulation of NBFRs in soil-crop system

Brominated flame retardants (BFRs) have excellent flame retardancy. It has become the most widely used flame retardant in the world. BFRs mainly include polybrominated diphenyl ethers (PBDEs) and polybrominated biphenyls (PBBs), tetrabromobisphenol A (TBBPA), hexabromocyclododecane (HBCD), etc. Since there is no chemical bond between novel brominated flame retardants (NBFRs) and the added carrier, at room temperature, it can easily enter the environment during the process of use, and migrate to groundwater, soil and plants. Finally, it is enriched in the human body through the food chain and has an adverse impact on human health.

NBFRs was used to study the accumulation in two common vegetables, cucumber and tomato. Cucumber and tomato are planted both inside and outside the greenhouse. After 40d, 70d and 90d, the plants and ground soils were collected. The following are the BCF data for the roots of the two vegetables in Table 3.4. The BCF of HBCD in tomato and cucumber are 0.86-2.1 and 1.1-2.3; The corresponding values for DBDPE were 0.37-5.7 and 2.4-9.3; for BTBPE, they were 1.4-5.7 and 1.3-6.8. The BCF of EHTBB in tomato and cucumber were 0-6.2 and 1.5-10; for HCDBCO, the figures were 0.082-0.9 and 0.71-1.9, respectively (Jiang, 2017).

Table 3.4. The BCF of NBFRs in tomato and cucumber roots

Plants	Organic pollutants	Inside Green House			Outside Green House		
		Seedling period	Fruiting period	mature period	Seedling period	Fruiting period	mature period
Tomato	HBCD	2.1	1.0	1.0	0.86	0.84	1.1
	DBDPE	1.3	0.38	0.37	4.1	3.9	6.9
	EHTBB	1.3	-	0	6.2	1.4	2
	BTBPE	1.5	1.4	1.4	4.8	5.7	1.7
	HCDBCO	0.11	0.66	-	0.082	0.24	0.90
Cucumber	HBCD	2.2	1.9	1.1	1.6	2.3	1.1
	DBDPE	4.6	5.7	2.4	9.3	5.6	2.7
	EHTBB	2.3	10	1.8	1.5	8.9	5.9
	BTBPE	3.2	1.3	2.4	1.4	6.8	4.7
	HCDBCO	0.71	1.1	0.75	1.9	1.0	1.0

***Source**: Jiang, P., 2017. Study on the Translocation of Novel Brominated Flame Retardants in Soil-Plant System. Desertation, Zheng Jiang University of Technology, China.*

3.1.2.4 The translocation and accumulation of antibiotics in soil-crop system

As veterinary additives, antibiotics are widely used in the breeding industry, and are released into soil and groundwater constantly. Persistent pollution effects and their potential environmental toxic effects have aroused widespread concern. In the study of Zhang (2018), typical antibiotics, such as chlortetracycline (CTC), sulfamethoxazole (SMZ), and gentamycin (GM) were used as model contaminants. The characteristic of plant absorption, transport and enrichment of typical antibiotics at high and low concentrations were studied. The representative soil in the north part of China and fast-growing vegetable (Brassica campestris) were selected for the study. The treatment concentrations of CTC, SMZ and GM were 1, 10 and 50mg/kg, respectively.

It can be seen from Table 3.5 that in the three treatment groups, the TF of CTC, SMZ and GM were 1.22-1.69, 1.126 and 1.226-1.889, respectively. The corresponding values of BCF were 0.044-3.84, 2.45 and 1.23-2.56. It was found that at the same concentration, the antibiotics absorption capacity of Chinese cabbage was shown as GM>SMZ>CTC, and the transport capacity was shown as GM>CTC>SMZ (Zhang, 2018).

Table 3.5. The TF and BCF of antibiotics in Chinese cabbage under different treatments in soil

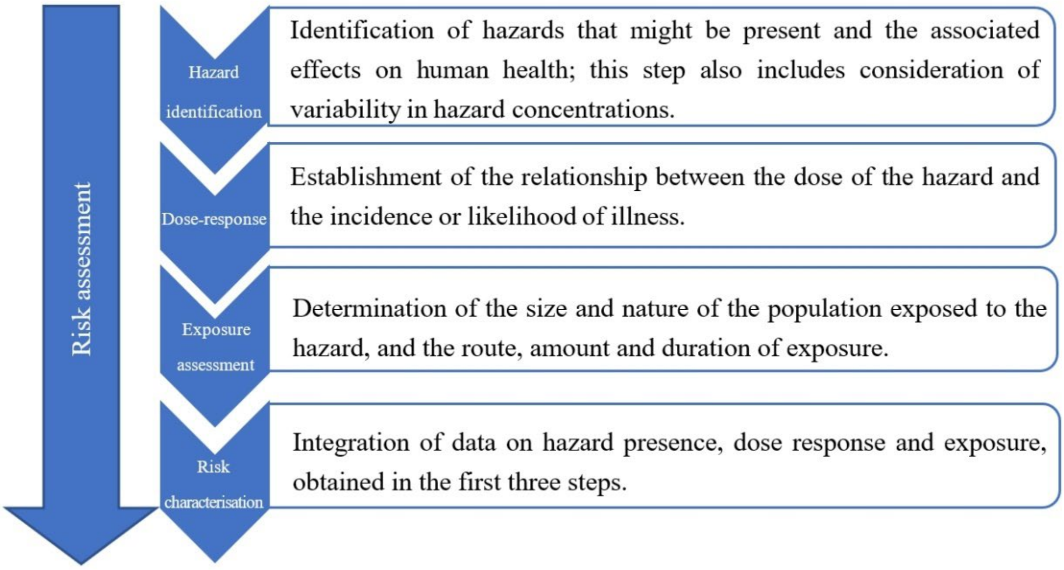
Antibiotics	Treatment（mg/kg)	Stem（mg/kg)	Root（mg/kg)	TF	BCF
CTC	1	0.0161±0.0002	0.0095±0.0008	1.6947	0.044
	10	0.2147±0.0092	0,174±0.0011	1.2339	1.510
	50	1.2477±0.0722	1.1182±0.0089	1.2254	3.841
SMZ	1	0.0867±0.0028	0.0770±0.0013	1.126	2.452
	10	-	-	-	-
	50	-	-	-	-
GM	1	0.1483±0.0057	0.0785±0.0063	1.889	1.237
	10	1.4061±0.0611	0.8220±0.0256	1.7106	2.240
	50	4.3531±0.1139	3.5507±0.1030	1.226	2.564

Source: *Zhang, S.C., Yao, H., Lu, Y.T., Shan, D., Yu, X.H., 2018. Reclaimed water irrigation effect on agricultural soil and maize (Zea mays L.) in northern China.Clean Soil Air Water.46(4):1800037 https://doi. org/10.1002/clen.201800037.*

3.1.3 Health Risk Assessment of ECs in Soil-Plant System

3.1.3.1 Health risk assessment models

In 1983, the USA National Academy of Sciences (NAS) and the National Research Council (NRC) proposed specific steps for health risk assessment. This health risk assessment method was aimed at protecting human beings from the hazards of chemical substances, and providing scientific basis for risk management. Since different countries have different laws and regulations on risk management, different health risk assessment methods are adopted worldwide. In order to clarify health risk assessment methods, the International Chemical Safety Programme has held several meetings since 1993, and finally agreed on the following basic framework for health risk assessment: hazard identification, dose effect assessment, exposure assessment, and risk characterization, or the “Four-Step Method”.



Identification of hazards that might be present and the associated effects on human health; this step also includes consideration of variability in hazard concentrations.

Establishment of the relationship between the dose of the hazard and the incidence or likelihood of illness.

Determination of the size and nature of the population exposed to the hazard, and the route, amount and duration of exposure.

Integration of data on hazard presence, dose response and exposure, obtained in the first three steps.

Figure 3.1. Four-Step Method of risk assessment

Source: *NWQMS (National Water Quality Management Strategy), 2006. Australian Guideline for waste recycling: managing health and environmental risks (phase 1).*

The accumulation of contaminants in plant tissues and soil pose potential risks to human health. Human body is exposed to contaminants mainly through three pathways: oral ingestion, derma contact and inhalation. With IARC, WHO, and US EPA-IRIS approaches, people are divided into two age subgroups: children (0-6 years) and adults (18-70 years). The ADD of contaminants from various exposure pathways is calculated using formulas (3.1-3.3). The parameters of the human health risk assessment models derive from USEPA (2004), US Department of Energy (USDOE) (2011), and China Environmental Protection Department (Duan, 2017).

$$ADD_{ing}=\frac{C\ \ \times IR\ \ \times EF\ \ \times ED}{BW\times AT} \tag{3.1}$$

$$ADD_{inh}=\frac{C\ \ \times IR\ \ \times CF\times EF\ \ \times ED}{BW\times AT} \tag{3.2}$$

$$ADD_{der}=\frac{C\ \ \times CF\times SA\times AF\times ABS\times EF\ \ \times ED}{BW\times AT} \tag{3.3}$$

where ADD_{ing}, ADD_{inh} and ADD_{der} are the average daily dose of exposure to a chemical (per kg of body weight) through the pathways of ingestion, inhalation and derma contact ($mg\cdot kg^{-1}\cdot day^{-1}$), respectively, which are suspected of having effects on human health over a long period of time; C is the contaminant concentration in water ($mg\cdot L^{-1}$), soil or plant tissues ($mg\cdot kg^{-1}$), respectively; IR is the daily intake of water ($kg\cdot L^{-1}$), soil or plant food ($kg\cdot day^{-1}$); CF is the conversion factor (10^{-6} $kg\cdot mg^{-1}$); EF is the frequency of food or soil exposure ($days\cdot years^{-1}$), respectively; ED is the duration of food and soil exposure (years), respectively; BW is the body weight (kg); AT is the average time of exposure (days); SA is the skin surface area available for contact with soil (cm^2); AF is the soil to skin adherence factor ($mg\cdot cm^{-2}\cdot day^{-1}$); and ABS is the absorption factor (unitless).

The exposure parameters are the most important in human health risk assessment models. Proper selection of the exposure parameters will significantly improve the accuracy of health risk assessment. The exposure parameters should be selected according to conditions such as residential area, living standards, dietary habits and physical characteristics. The exposure factor handbooks of the United States, Europe, Japan and Korea have played an important role in improving the accuracy of population exposure assessment.

USEPA has established the Integrated Risk Information System (IRIS) which includes the pathology study data of 500 plus common toxic elements and chemical compound. The reference dose (*RfD*) represents the Acceptable Daily Dose (ADD), which demonstrates the hazard degree of a certain toxic substance, with the unit of $mg\cdot kg^{-1}\cdot day^{-1}$. When the dose of exposure to a toxic substance exceeds the *RfD*, it is considered that there may be concern for potential health effects. Equation 3.4 of the quantification coefficient Hazard Quotient (HQ) is to used to calculate non-carcinogenic risk. Hazard Index (HI) is the sum of the HQs for several chemicals. If the HQ or HI equals or exceeds 1, there may be concern for potential health effects.

$$HQ=\frac{ADD}{RfD} \tag{3.4}$$

The incremental cancer risk (ILCR) is an indicator of carcinogenic risk to human health, i.e., the incremental cancer risk caused by human exposure to a certain dose of a carcinogen over a certain period (e.g., lifetime), and is set by USEPA at 10^{-6} for the human health standard cancer risk interception value, calculated as follows:

$$ILCR = CSF \times ADD \tag{3.5}$$

where CSF is the carcinogenic slope factor, kg·d/mg.

3.1.3.2 Examples of health risk assessment model application

Based on the above risk assessment method, researchers have analyzed the human health risk induced by contaminants in soil-plant system. The following is an example of assessing the human health risks caused by the ingestion of NP and BPA.

In Professor Wu Wenyong's research project, pot experiments of food and vegetable crops were selected to study the occurrence and distribution of emerging chemicals in soil-plant system under long-term reclaimed water irrigation. NP has been detected in various plants, with NP concentrations ranging from 0.23 to 0.77 mg/kg in wheat grains, 0.036-0.054 mg/kg in edible parts of lettuce, and 0.015-0.028 mg/kg in eggplant fruits. BPA was found to range from 0.0581 to 0.3773 mg/kg in color peppers and was not detected in both wheat and corn grains. According to the results of this study, the highest concentrations of NP and BPA in grain crops and vegetable crops were selected to evaluate the health risk due to oral ingestion for the most adverse situation. The risk values calculated by the afore-mentioned health risk model are listed in Table 3.6. The results show that for children and adults, the noncancer hazard index (HI) for both NP and BPA induced by ingesting food crops are 0.00455 and 0.00783, respectively, which are less than 1. The results suggest that in this case, the health risk of exposure to NP and BPA via ingestion is acceptable.

Table 3.6. The HQ or HI for children and adults exposed to NP and BPA

emerging chemicals	**plants**	**Children**		**Adult**	
		HQ	**HI**	**HQ**	**HI**
NP	grain crops	3.98×10^{-3}	4.02×10^{-3}	6.69×10^{-3}	6.75×10^{-3}
	vegetable crops	3.48×10^{-5}		6.95×10^{-5}	
BPA	grain crops	0	5.39×10^{-4}	0	1.07×10^{-3}
	vegetable crops	5.39×10^{-4}		1.07×10^{-3}	
NP and BPA	food crops	/	4.55×10^{-3}	/	7.83×10^{-3}

***Source**: Author's own elaboration.*

3.1.4 The classification of health risks

In theory, the standard value for non-carcinogenic risk of chemical substances is set as 1. When the value is less than 1, there will be no significant non-carcinogenic health effects on the exposed population. For carcinogenic risk, the US EPA has set 10^{-6} as the lower limit of acceptable risk level, and 10^{-4} as the upper limit. When the carcinogenic risk is lower than or equal to 10^{-6}, it is considered negligible; when the risk is between 10^{-6} and 10^{-4}, it is considered acceptable; when the value is higher than 10^{-4}, the risk is considered unacceptable.

3.2 Crop Classification of International Standards

For the recycling of wastewater, there is no unified Guidelines worldwide (Li et al., 2009a, Li et al., 2009b, Li et al., 2014). Parameters and values of reclaimed water quality standards are related to their classifications based on irrigation purposes, crop types, and irrigation methods. The standard classifications of different organizations and countries are of local characteristics (Zhao et al., 2022). Table 3.7 summarizes the classifications of reclaimed water irrigation standards of some organizations and countries.

The purposes of reclaimed water irrigation involve farmland irrigation and green space or landscape irrigation. Farmland irrigation is the most widely covered topic, as in the standards set by US, China, Spain and Saudi Arabia (EPA, 2012, AQSIQ, 2007, ASERSA, 2007, MOWE, 2000). The European Union, Australia, France, Greece, Portugal and Jordan talk about more specific agricultural or other uses (EP & CEU, 2020, EPHCA, 2006, MSAPHF, 2014, MEECCG, 2011, IQP,2005, JISM, 2006). Green space or landscape irrigation are often listed as a subordinate branch of municipal miscellaneous uses, as in the American and Spanish standards (EPA, 2012, ASERSA, 2007), but they are separately classified as an important category in countries such as China, Greece and Japan (AQSIQ ,2010, MEECCG, 2011, MLIT, 2005). Landscape irrigation is also listed separately in the Australian Guidelines (EPHCA, 2006).

When reclaimed water is used for agricultural irrigation, it needs to be differentiated according to the type of crop. Different crop types imply different crop usages, crop characteristics, and risks for people exposed to crop. Organizations and Countries such as EU, USA, Australia, Cyprus, France, Greece, Portugal, and Spain divide edible crops into food crops, processed edible crops, and unprocessed / processed commercial food crops (EP & CEU, 2020, EPA 2012, EPHCA, 2006, MANREC, 2005, MSAPHF, 2014, MEECCG, 2011, IQP, 2005, ASERSA, 2007). According to the Jordanian standards, reclaimed water is not allowed to be used to irrigate vegetables that are eaten raw, and irrigation must be stopped two weeks before harvesting if reclaimed water is used to irrigate fruit trees, with the exclusion of fallen fruits that are in contact with the soil (ISMJ, 2006). China divides crops into dryland cereal and oil crops (wheat, soybean, corn, etc., which rely on natural precipitation and artificial irrigation in arid and semi-arid areas), and paddy fields cereals (rice, etc., which grow in deep and fertile soil, and needs a certain water layer), and open-field vegetables (except greenhouse vegetables that need to be processed, cooked and peeled) (AQSIQ, 2007). Cereals and oil crops are also specified in Portuguese and Spanish standards. France, Portugal and Spain have classifications that take into account vegetables and fruit trees (IQP, 2005, ASERSA, 2007, MSAPHF, 2014).

For inedible crops, EU, AUS, Cyprus, Greece, Portugal, Spain, etc., all cover fodder crops (EP & CEU, 2020, EPHCA, 2006, MANREC, 2005, MEECCG, 2011, IQP, 2005, ASERSA, 2007), Chinese standards cover fiber crops (cotton, jute, flax and other crops that produce plant fiber) (AQSIQ, 2007), and Portugal also covers crops for textile (IQP, 2005).

The classification by countries such as the US is only based on whether the crop is edible or needs to be processed, which is more from the perspective of consumers. However, for the categorization of dryland and paddy fields in China (AQSIQ, 2007) and the classification by France, Portugal and Spain, more factors from both the consumer and producer perspectives are taken into consideration, such as the purposes of the textile and food, the difference of growth environment the processing methods (oil extraction, cooking, and peeling) (MSAPHF, 2014, IQP, 2005, ASERSA, 2007).

WHO, China, USA, Israel, Cyprus, Greece, Portugal, Spain, Saudi Arabia all have unrestricted irrigation and restricted irrigation categories (WHO, 2006, AQSIQ, 2010, EPA 2012, WAI, 2010, MANREC, 2005, MEECCG, 2011, IQP,2005, ASERSA, 2007, JISM, 2006). The unrestricted irrigation defined by WHO mainly refers to the freedom of contact between crops and consumers (WHO, 2006). The definitions of restricted and unrestricted irrigation in other standards are similar, but they will be described in more detail on specific occasions. For instance, the urban reuse of reclaimed water in the US has the two categories of unrestricted irrigation and restricted irrigation. The unrestricted irrigation is described as the use of reclaimed water for nonportable applications in municipal settings where public access is not restricted, and the restricted irrigation is defined as the use of reclaimed water for nonportable applications in municipal settings where public access is controlled or restricted by physical or institutional barriers, such as fencing, advisory signage, or temporal access restriction. The urban uses refer to the irrigation of places or areas such as recreational field, golf course, landscape, parks and recreation centers, athletic fields, school yards and playing fields (EPA, 2012). In China, the reuse of urban recycled water in green space irrigation is divided into unrestricted green space and restricted green space, similar to that in the United States. Unrestricted green space refers to green space that is completely open to the public, such as parks, residential areas and campus green space, etc. Restricted green space refers to green space that restricts public access, such as highway green belts, cemeteries and other green space (AQSIQ, 2010).

Compared with agricultural irrigation, the classification of which has laws to follow, that of green landscape irrigation is chaotic. In addition to the common municipal reuse categories of green space irrigation such as gardens, green belts, and landscape irrigation, China also discusses, alongside the reuse of reclaimed water in agricultural and pasture irrigation, the reuse in forestry irrigation which refers to irrigation of forests, ornamental plants, and nurseries (MWRC, 2006). Sprinkling water in the Japanese standards refers to the reuse of reclaimed water for irrigating trees, plants and lawns or flushing roads (MLIT, 2005). Greece considers golf course as periurban green space and its irrigation as urban uses (MEECCG, 2011). Spain defines golf course irrigation as recreational uses (ASERSA, 2007). The French, Spanish and Jordanian standards all take into account horticultural uses such as the irrigation of nurseries, floral crops, cut flowers, and ornamental crops (MSAPHF, 2014, ASERSA, 2007, ISMJ, 2006).

In terms of irrigation methods, WHO believes the standards can be moderately relaxed under drip irrigation conditions (WHO, 2006). The EU also imposes restrictions on drip irrigation or other irrigation methods which avoid direct contact of reclaimed water with edible parts for food crops, processed food crops and non-food crops (EP & CEU, 2020). In its sections of urban reuses, the Greek standards require the prohibition of sprinkler irrigation, and take a moderately relaxed approach towards drip irrigation (MEECCG, 2011). The Spanish standards call for broader turbidity limits when it comes to drip or micro-sprinkler irrigation (in Table 3.10) (ASERSA, 2007). The Jordanian standards ask for the prohibition of sprinkler irrigation unless it is for golf courses which must be done at night (ISMJ, 2006). With their development and extension, irrigation methods should be given more attention when formulating reclaimed water irrigation standards.

Table 3.7. Classification of Reclaimed Water Irrigation Standards

Country/ Organization	Classification of reclaimed water irrigation standards	References
WHO	Unrestricted irrigation: root crops, leaf crops, drip irrigation, high-growing crops Restricted irrigation: labor-intensive, high-contact agriculture, highly mechanized agriculture Localized (drip) irrigation: high-growing crops, low-growing crops (the parameter limit can be relaxed)	WHO, 2006
EU	A: All food crops consumed raw where the edible part is in direct contact with reclaimed water and root crops consumed raw B: Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals (all irrigation methods) C: Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals (drip irrigation or other irrigation method that avoids direct contact with the edible part of the crop) D: Industrial, energy and seeded crops	EP & CEU, 2020 CEU, 1991
USA	Urban reuse: Unrestricted:The use of reclaimed water in nonpotable applications in municipal settings where public access is not restricted Restricted: The use of reclaimed water in nonpotable applications in municipal settings where public access is controlled or restricted by physical or institutional barriers, such as fencing, advisory signage, or temporal access restriction Agricultural reuse Food crops: The use of reclaimed water for surface or spray irrigation of food crops which are intended for human consumption, consumed raw Processed food crops: The use of reclaimed water for surface irrigation of food crops which are intended for human consumption, commercially processed. Non-food crops: The use of reclaimed water for irrigation of crops which are not consumed by humans, including fodder, fiber, and seed crops, or to irrigate pasture land, commercial nurseries, and sod farms.	EPA, 2012
Japan	Sprinkling water: green belt, lawn	MLIT, 2005
China	Farmland irrigation Fibre crops Dry grain Wet grain Open-air vegetables Green space irrigation Unrestricted access green space irrigation (green space completely open to the public, such as parks, residential areas and campus green space) Restricted access green space irrigation (green space restricted to the public, such as the green separation belt of highway, cemetery and other green space) Forestry irrigation	MWRC, 2007 AQSIQ, 2007 AQSIQ, 2020
AUS	Commercial food crops consumed raw or unprocessed Commercial food crops Nonfood crops Pasture or fodder crop irrigation (including hay, silage and commercial fodder production). Limited withholding period Pasture or fodder crop irrigation (including hay, silage and commercial fodder production). Withholding period Landscape irrigation	EPHCA, 2006
Russia	Unrestricted irrigation: technical crops, cereals, feed crops and woody shrubs; perennial herbs (alfalfa, clover, invertebrate, meadow fox, meadow Timofievka, meadow oats, hedgehogs, double handle and reed oats, etc.), and annual herbs and weeds; forest belts, nurseries, nurseries for planting ornamental and berry crops, and plantations for intensive production of wood, willow and protective forests; prohibited to grow vegetable crops, including potatoes, berries, fruits, melons and salads.	MHR, 1996
Israel	Unrestricted irrigation: conventional-from district engineer: cotton, wheat, forage, feed crops; crops which undergo industrial processing; Irrigation of non-recreational forest land; special-from national Ministries: vegetables for consumption uncooked	WAI, 2010
Cyprus	All crops (it is forbidden to irrigate leafy vegetables, bulbs and tubers eaten by eggs.) Vegetables eaten cooked (potatoes, zucchini and sweet potatoes) Crops for human consumption amenity areas of limited public access Fodder crops Industrial crops	MANREC, 2002 MANREC, 2005
France	A: Vegetable, fruit and vegetable crops not processed by an appropriate industrial heat treatment (except watercress); green space open to the public B: Vegetable, fruit and vegetable crops transformed by an adapted industrial heat treatment; pasture; flowers sold cut; fresh fodder C: Nurseries and shrubs and other floral crops; other cereal and forage crops; fruit trees D: Short-rotation or very short-rotation coppice, with controlled public access	MSAPHF, 2014
Greece	Restricted irrigation: Unrestricted irrigation Urban uses and periurban green	MEECCG, 2002

Country/ Organization	Classification of reclaimed water irrigation standards							References
	Areas where public access is not expected, fodder and industrial crops, pastures, trees (except fruit trees), provided that fruits are not in contact with the soil, seed crops and crops whose products are processed before consumption. (Sprinkler irrigation is not allowed)	All crops such as fruit trees, vegetables, vines or crops whose products are consumed raw, greenhouses. Allows the application of various methods of irrigation, including sprinkler irrigation.	Cemeteries, golf courses, public parks, freeway embankments, recreational facilities, fire protection, street cleaning and decorative; including groves and forests (Sprinkler irrigation is not allowed)					MEECCG, 2011
Italy	A: Food crops to be consumed raw, whose edible part is in direct contact with refined waters and plants root to be eaten raw. All irrigation techniques are allowed.	B: Food crops to be consumed raw whose edible part is produced above the ground level and is not at direct contact with refined water; food crops to be transformed; crops for animal feed (pasture and forage crops); crops not for food. All irrigation techniques are allowed.	C: Food crops to be consumed raw whose edible part is produced above the ground level and is not at direct contact with refined water; food crops to be transformed; food crops not to be transformed, including crops for animal feed (dairy or beef animals). Drip irrigation-other technique avoiding direct contact with edible parts of the crop.	D: Industrial, energy and seed crops. All irrigation techniques are allowed.				MEI, 2023
Portugal	A: Vegetables to be eaten raw	B: Public parks and gardens, sport lawns, forest with public easy access	C: Vegetables to be cooked, forage crops, vineyards, orchards	D: Cereals (except rice), vegetables for industrial process prior to consumption, crops for textile industry, crops for oil extraction, forest and lawns located in places of difficult or controlled public access.				IQP,2005
Spain	Urban uses		Agricultural uses			Recreational uses	Environmental uses	ASERSA, 2007
	Q1: Irrigation of private gardens	Q2: Landscape irrigation of urban areas (parks, sports grounds and similar)	Q1: Crop irrigation using a system whereby reclaimed water comes into direct contact with edible parts of crops to be eaten raw	Q2: Irrigation of crops for human consumption using application methods that do not prevent direct contact of reclaimed with edible parts of the plants, which are not eaten raw but after an industrial treatment process; irrigation of pasture land for milk- or meat-producing animals	Q3: Localized irrigation of tree crops whereby reclaimed water is not allowed to come into contact with fruit for human consumption; irrigation of ornamental flowers, nurseries and greenhouses whereby reclaimed water does not come into contact with the crops; irrigation of industrial non-food crops, nurseries, silo fodder, cereals and oilseeds	Golf courses irrigation, if irrigation water is directly applied to soil (drip irrigation, micro-sprinkler), criteria for Agricultural uses Q3 shall apply	Irrigation of woodland, green areas and other space not accessible to the public; silviculture	
Jordan	A: Cooked vegetables, parks, playgrounds and sides of roads within city limits (It is prohibited to use sprinkler irrigation except for irrigating golf courses and in that case irrigation should practice at night and the sprinklers must be of the movable type and not accessible for day use.)	B: Fruit trees, sides of roads outside city limits, and landscape	C: Field crops, industrial crops and forest trees	Cut flowers				ISMJ, 2006
Saudi Arabia	Urban use: Trees, shrubs and green spaces planted on streets, parks, entertainment places and highways.		Agricultural uses					MOWE, 2000
	Unrestricted irrigation	Restricted irrigation	Unrestricted irrigation: All crops	Restricted irrigation: Tubers, vegetable crops, irrigate all types of crops, whether fresh or fruit contact cooked water plants.				

***Source**: Author's own elaboration.*

In addition, Jordan divides its standards into standards group and Guidelines group. The former require strict compliance with the limit values of basic water quality parameters, the latter is used to guide the control of heavy metals and other meticulous water quality parameters (ISMJ, 2006). China divides the parameters into two major categories: the basic control items and the selective control items (AQSIQ, 2007, AQSIQ, 2010).

3.3 Suggested Plant Classification

As shown in table 3.8, all crop classifications are related to health risk of exposure, such as crops eaten raw or processed, restricted crops or unrestricted crops, edible part with or without contact with reclaimed water, and green space with easy or difficult public access. Based on their health risk of exposure, the three classes of A, B and C are proposed in table 3.8, with the corresponding indicative technology.

Table 3.8. Suggested plant classification for reclaimed water irrigation

Plant class	Plant category	Treatment
A: high exposure risk group	All food crops consumed raw or unprocessed	Secondary or tertiary treatment, filtration, and disinfection
B: medium exposure risk group	Processed food crops, fodder crop; parks and gardens, sport lawns, forest with public easy access	Secondary treatment, and disinfection
C: low exposure risk group	Nonfood crops; parks and gardens, forest and lawns rarely accessed by the public or located in places of difficult or controlled public access	Secondary treatment, and disinfection

***Source**: Author's own elaboration based on summary of various research results and documents.*

* * *

4. Feasibility Evaluation of Irrigation Area

4.1 Feasibility Mapping Using the Risk Assessment Model

Reclaimed water contains common inorganic pollutants such as nitrogen, phosphorus, and heavy metals, as well as trace amounts of toxic and harmful pollutants such as persistent organic pollutants (POPs) and endocrine disruptors (EDCs), which will increase the risk of groundwater pollution (Wu et al., 2020). The risk assessment model can be used for calculating the risk of the target compound based on its toxicity, migration and degradation. The model results of groundwater pollution risk caused by reclaimed water irrigation (RWI) could be expressed in a feasibility map. Feasibility map plays an important role in site selection and evaluation.

Based on the typical risk indices such as intrinsic vulnerability, hazard qualification and groundwater value, Wu et al. (2020) applied the model of groundwater pollution risks caused by RWI. Intrinsic vulnerability index depends on the geological, hydrological and hydrogeological characteristics of a study area as well as natural contamination (Zwahlen, 2003; Barzegaret al., 2020), and is calculated widely by the DRASTIC model (Aller et al., 1987) using the following Eq. (4.1):

$$IVI = D_w D_r + R_w R_r + A_w A_r + S_w S_r + T_w T_r + I_w I_r + C_w C_r \qquad (4.1)$$

where the DRASTIC model includes 7 parameters: depth of groundwater (D_r, m), recharge (R_r, mm/a), aquifer media (A_r), soil media (S_r), topography slope (T_r), impact of the vadose zone media (I_r), and hydraulic conductivity (C_r, mm/s). These parameters are of three types: 1) impact assessment factors for pollution input, including the topographic slope (T_r) and recharge (R_r); 2) impact assessment of the vulnerability of the vadose zone, including soil types (S), impact of the vadose zone (I_r), and depth of groundwater (D_r); and 3) impact assessment factors for migration and dispersion in the saturated zone, including the aquifer media (A_r) and hydraulic conductivity (C_r). D_w, R_w, A_w, S_w, T_w, I_w, and C_w are the weights of the ratings for D_r, Rr, A_r, S_r, T_r, I_r, and C_r, respectively.

Many studies have simplified the model's parameters to make it more practical (Zhong, 2005; Panagopoulos et al., 2006; Nobre et al., 2007). For example, Wu et al. (2014) revised the DRASTIC model (Eq. 4.2) Based on the hydrogeological conditions of alluvial-diluvial fan plains.

$$IVI = 4.4D_r + 2.9R_r + 3.1A_r + 2.2S_r + 5I_r \qquad (4.2)$$

Pollution hazard index refers to the potential degree of harmfulness to groundwater that natural and man-made pollution sources will cause, and it is mainly determined by the toxicity and quantity of dangerous substances (Zwahlen, 2003). The main process of hazard quantification is divided into the following four steps: 1) to construct a hierarchical structure based on the relative importance or focus of the characteristic pollutants for the environment; 2) to establish a component judgement matrix; 3) to perform hierarchical ranking and consistency testing; and 4) to obtain the weights for the three attributes of toxicity, mobility, and degradability. The hazard (Si) scoring for the toxicity, mobility, and degradability of irrigation with reclaimed-water-derived characteristic pollutants using the following equations:

$$S_i = \sum_{i=1}^{n} C_i \times F_i \qquad (4.3)$$

$$F_i = W_i \times Q_i \qquad (4.4)$$

$$W_i = \frac{q_i}{s_i} \qquad (4.5)$$

$$C_i = T_i \times T_w + M_i \times M_w + D_i \times D_w \qquad (4.6)$$

Where S_i is the quantitative rating of the ability of the n types of characteristic pollutants in reclaimed water to pollute the groundwater environment, and is referred to as pollution source hazard; C_i is the quantitative rating of the three attributes (toxicity, mobility, and degradability) of the i_{th} characteristic pollutant and is referred to as the hazard of the characteristic pollutant, which is listed in Table 4.1; F_i is the amount of the i_{th} characteristic pollutant that can enter the groundwater environment and is referred to as the emissions; W_i denotes the above-standard level of the i_{th} characteristic pollutant in a given plot; Q_i denotes the rating of the irrigation infiltration recharge for the i_{th} characteristic pollutant, which is calculated based on the ratings of R_r displayed in Table 4.1; q_i is the concentration of the i_{th} characteristic pollutant, which is obtained from the measurement of the collected water samples; s_i denotes the standard value for the i_{th} characteristic pollutant, which was shown in Table 4.1; and T_i, M_i, and D_i denote the toxicity rating, mobility rating, and degradability rating of the i_{th} characteristic pollutant. T_w, M_w, and D_w are the weights of the ratings for T_i, M_i, and D_i, respectively.

Groundwater value is related to multiple factors such as the ecological, social and economic values, providing the present and future value of exploiting groundwater resources (Saidi al., 2011; Wang et al., 2012). In a typical study of groundwater pollution risk, the groundwater value is mainly determined by groundwater storage and groundwater quality. In most studies, three factors are considered, including water yield property of aquifer, groundwater quality, and groundwater protection areas.

$$E_i = O_w \times O_r + P_w \times P_r + Q_w \times Q_r \tag{4.7}$$

Where E_i denotes the groundwater value; O_r, P_r, and Q_r denote the quantity of water in the aquifer, the groundwater quality, and the rating of the groundwater source protection zone, respectively; and O_w, P_w, and Q_w denote the weights of the ratings for O_r, P_r, and Q_r, respectively.

Groundwater pollution risk assessment is composed of intrinsic vulnerability index (IVI_i), groundwater pollution hazard (S_i), and groundwater value (E_i). It is calculated as the sum of the products of these three components and their respective weights (IVI_w, S_w, and E_w).

$$V = IVI_i \times IVI_w + S_i \times S_w + E_i \times E_w \tag{4.8}$$

Where V is the groundwater pollution risk; IVI_i, S_i, and E_i are the intrinsic vulnerability index of the groundwater, the groundwater pollution hazard, and the rating of groundwater value parameter, respectively; and IVI_w, S_w, and E_w are the weights of the ratings for IVI_i, S_i, and E_i, respectively.

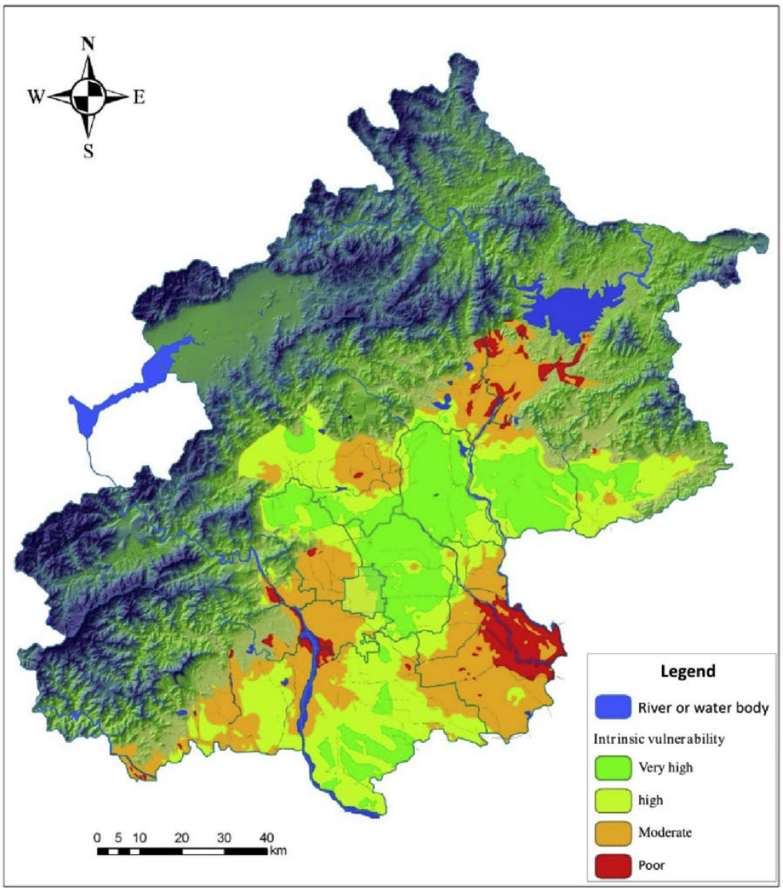


Figure 4.1. Groundwater pollution risk map of the study area (***Source***: *Author's own elaboration*)

After risk assessment calculation, a regionalization map of low, moderate and high pollution risks is drawn. This map is helpful to plan and design pollution prevention reuse systems.

4.2 Feasibility Evaluation Using the Multi-Parameter Evaluation Method

Multi-parameter evaluation is one typical method for feasibility evaluation and has been used to evaluate the feasibility of reclaimed water irrigation projects. For instance, the integrated geospatial multi-parameter decision analysis with the analytical hierarchy process has been implemented to evaluate the potentiality of reclaimed water use for agricultural irrigation (Paul et al. 2020). Normally, the main parameters for reclaimed water irrigation are land slope, soil and geology, and groundwater depth (Fuller and Warrick, 1985; Liu et al., 2009). The corresponding scores of these parameters are shown in Table 4.1.

Table 4.1. Parameters for reclaimed water irrigation district

Groundwater contamination risks	**Control indicators for groundwater protection**		
	Groundwater depth （*D*）	**Permeation rate in aeration zone （*K*）**	**Land slope （*1*）**
Low	$D \geq 8$m	$K < 0.5$m/d	$I < 2$ %
Moderate	3m $\leq D <$ 8m	0.5m/d $\leq K < 0.8$m/d	2% $\leq I < 6$ %
High	$D < 3$m	$K \geq 0.8$m/d	$I \geq 6$ %

***Source**: Author's own elaboration.*

Sloping land increases water loss and soil erosion during irrigation or rainy seasons, and accelerates the movement of pollutants to water bodies outside the reclaimed water irrigation district, which could further lift the operating costs. Therefore, the slope of the irrigation district should be less than 15% (Crites, 1985), best management practices should be employed to minimize runoff. Improper use of reclaimed water irrigation on sloping land is a significant non-point source of water pollution in agriculture.

Important determinants of the potential for groundwater pollution from reclaimed water irrigation are the structure of the soil aeration zone, depth and permeability coefficient. For example, in Beijing, the soil at the upper stream of the alluvial fan is highly permeable; therefore, leaching in the reclaimed water irrigation could accelerate groundwater contamination. As a result, reclaimed water irrigation is not recommended in the upper stream regions; in contrast, the soil is less permeable in the middle-reach and lower-stream regions, so reclaimed water could be used for irrigation with less impact on groundwater. The depth of water table is an important factor for determining the risks of groundwater contamination from reclaimed water irrigation.

Table 4.2. Planning considerations for different evaluation results

Groundwater contamination risks	**Regionalization of irrigation area**	**Planning considerations**
Low	Feasible	Groundwater contamination by irrigation infiltration is not a major concern. The use of reclaimed water in crop and green space irrigation should be encouraged. Reclaimed water can be distributed by rivers, canals or pipes. Plants can be irrigated through surface irrigation, drip irrigation or sprinkler irrigation.
Moderate	Control	Reclaimed water should be distributed by lined canals or pipes to control seepage loss to groundwater. Plants can be irrigated by highly efficient surface irrigation, drip irrigation or sprinkler irrigation with low seepage loss to lower contamination risk.
High	Unfeasible	RWI should be prohibited to avoid groundwater contamination.

***Source**: Author's own elaboration.*

‘High’ indicates that this type of terrain is not appropriate for the use of reclaimed water due to the need for preventing long-term impacts on groundwater. ‘Control’ indicates that reclaimed water irrigation can be applied on this type of terrain, but seepage loss should be controlled in water delivery and distribution. ‘Low’ indicates that this terrain is appropriate for reclaimed water irrigation, but the optimum management practices should be adopted. Reclaimed water irrigation should be prohibited near urban central waterworks and water sources.

4.3 Engineering Considerations for Different Allocation

According to the evaluation results, RWI area could be divided into preferential zones, feasible zones and unfeasible zones. Different zones have different levels of vulnerability to groundwater contamination. Proper distribution and irrigation methods should be selected according to the evaluation results.

* * *

5. Irrigation System Design

5.1 General layout

Reclaimed water irrigation projects are usually composed of pretreatment projects, storage projects, distribution projects, irrigation projects and so on. Whether pretreatment and storage projects are necessary depends on effluent quality and planned irrigation area. Pretreatment projects are for improving effluent quality and thus expanding the variety of recipient crops; storage projects are for regulating water supply and thus enlarging the irrigated area. Percolation treatment has been applied to sewage using land infiltration, surface seepage and oxidation ponds in the Werribee farm in Melbourne, Australia. Soil Aquifer Treatment (SAT) has been constructed to purify reclaimed water and regulate water underground in Dan regional reclamation project (Shafdan), Israel. In the Nanhongmen irrigation area of Beijing, China, water is distributed via rivers and canals from urban area upstream to agricultural area downstream, and Yanggezhuang wetland has been constructed to purify and store reclaimed water for irrigation.

Systematical layout of different projects is a key to ensuring safe reuse of reclaimed water. Six tech modes of CR, PR, SR, WR, DR and TR are summed in table 5.1.

Table 5.1. Six tech modes of reclaimed water irrigation.

Items	**"CR" mode (River Cycled Reuse)**	**"PR" mode (Storage Pond Reuse)**	**"SR" mode (Soil Aquifer Treatment Reuse)**	**"WR" mode (Wetland Treatment Reuse)**	**"DR" mode (Direct Reuse)**	**"TR" mode (Tertiary Treatment Reuse)**
Wastewater treatment	Secondary treatment	Secondary treatment	Secondary treatment	Secondary treatment	Secondary treatment	Tertiary treatment
Pretreatment or storage	Reclaimed water is distributed, purified and cycled through natural rivers from upstream urban area to downstream agricultural area	Reclaimed water is stored and improved in storage pond	Reclaimed water is purified and stored in groundwater by soil aquifer treatment system	Reclaimed water is treated and stored by wetland treatment system	Reclaimed water is directly distributed to irrigation system	No pretreatment is required for reuse under tertiary treatment, and storage is necessary in most cases
Distribution system	River and canals	Canals or pipes	Canals or pipes	Canals or pipes	Canals or pipes	Canals or pipes
Irrigation methods	Surface irrigation, drip irrigation	Surface irrigation, drip irrigation	All irrigation methods	All irrigation methods	Surface irrigation, drip irrigation	All irrigation methods
Plants	Processed food crops/non-food crops/forests/green space	Processed food crops/non-food crops/forests/green space	Any crops	Processed food crops/non-food crops/forests/green space	Processed food crops/non-food crops/forests	Any crops

***Source**: Author's own elaboration.*

Under the CR mode (Figure 5.1), the reclaimed water is distributed and purified through natural rivers from urban areas upstream to agricultural areas downstream. The mode not only helps recover surface water in water-stressed urban and suburban areas, but also improves reclaimed water quality and stores reclaimed water in natural river systems. This natural cycle needs ecological water for filtration and evaporation, and thus water balance calculation is necessary for such a mode. Reclaimed water resource with stable and flow rate is required in planning such reuse systems. Integrative management of reclaimed water and rainwater is important to protect urban areas against floods. Surface irrigation systems or drip irrigation systems are used preferentially for processed food crops, non-food crops, forests and green spaces.

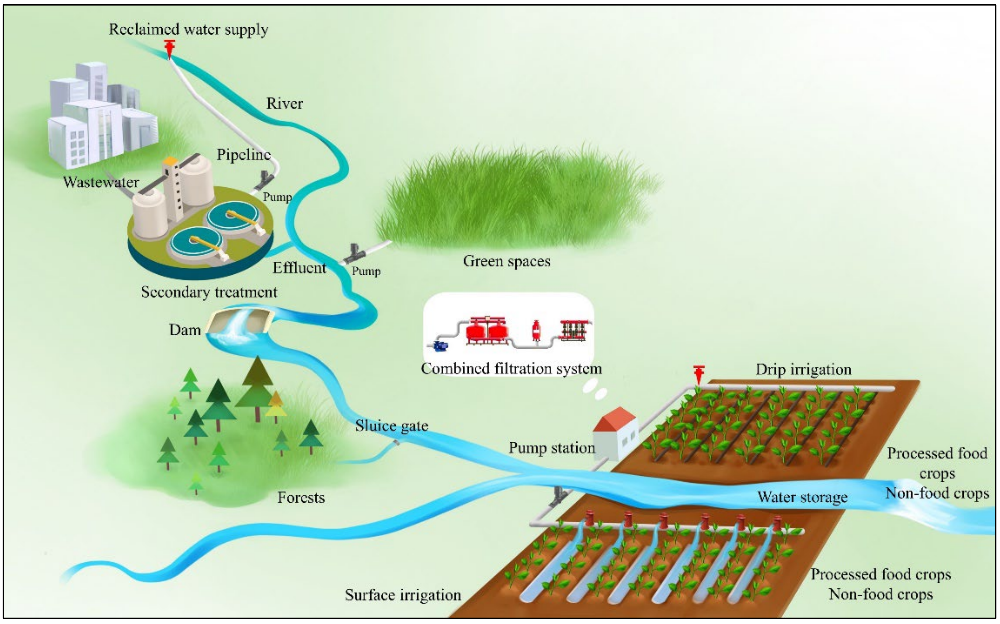


Figure 5.1. Sketch map of "CR" mode (***Source****: Author's own elaboration)*

Under the PR mode (Figure 5.2), the effluent is stored and improved in storage ponds or reservoirs to regulate water supply for the period of high crop water requirement. Based on the duration of storage, there are short-term storage and long-term storage. Short-term storage is usually designed to meet water demand within one duration of rotational irrigation, commonly less than 1-2 weeks. Long-term storage is planned for several durations of rotational irrigation, commonly lasting several months to half year. Surface storage reservoirs have proved to be efficient in reducing irrigation risks by removing organic matters, nitrogen, phosphorus, parasites and bacteria (Lazarova, 2001; Juanico, 2002). It is also important to avoid algae bloom with additional measures during storage. Surface irrigation systems or drip irrigation systems are used preferentially for processed food crops, non-food crops, forests and green spaces.

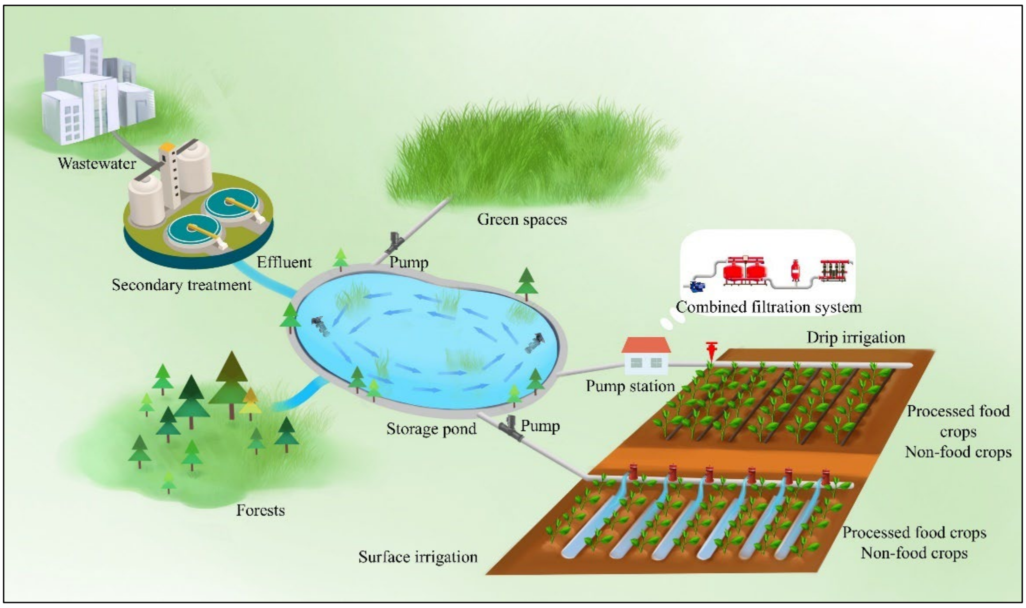


Figure 5.2. Sketch map of "PR" mode (***Source****: Author's own elaboration)*

Under the SR mode (Figure 5.3), the effluent is purified by the Soil Aquifer Treatment (SAT) System and then used for irrigation; SAT provides advanced treatment prior to effluent reuse for unrestricted irrigation. SAT projects are composed of recharge basins, observing wells and recovery wells. Flooding and drying cycles are crucial to SAT operation as they enable the aeration of the soil underneath the SAT basin and maintain steady infiltration rates (Negev et al., 2020). SAT effectively removes organics, nutrients, heavy metals, microorganisms, and micropollutants thanks to its contaminant removal mechanisms, such as physical filtration, biodegradation, adsorption, chemical precipitation, ion exchange, and dilution (Fox et al., 2001; Aharoni et al., 2011; Wei et al., 2016). Reclaimed water purified by SAT can be used to irrigate all types of crops within a full range of irrigation systems.

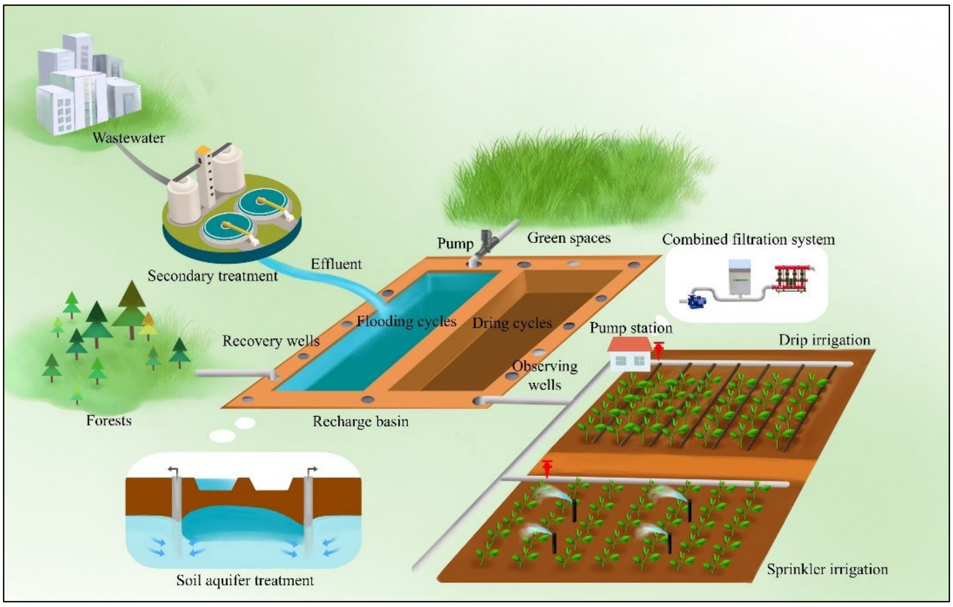


Figure 5.3. Sketch map of “SR” mode *(**Source**: Author's own elaboration)*

Under the WR mode (Figure 5.4), the effluent is treated and stored by wetland treatment system and then used for irrigation. Wetland Treatment Systems (WTS) are composed of retention basins, granular filling media, planted vegetation and storage ponds (in case that water supply regulation is required). WTS improves reclaimed water quality with the synergy of physical, chemical, and biological measures. The planted vegetation contributes to wastewater treatment through the assimilation of nutrients, the support to the development of biofilms, and the oxygenation of the root’s environment (Wang et al., 2018; Sandoval, et al., 2019;). The filling medium may also contribute directly to wastewater treatment through physical and chemical processes, such as filtration, adsorption, precipitation, as well as through its support to the development of biofilms (Rajan et al., 2018; Sanjrani et al., 2020; Pinho & Mateus, 2021). WTS discharge is a feasible source of irrigation water for processed food crops, non-food crops, forests, and green space in all types of irrigation systems.

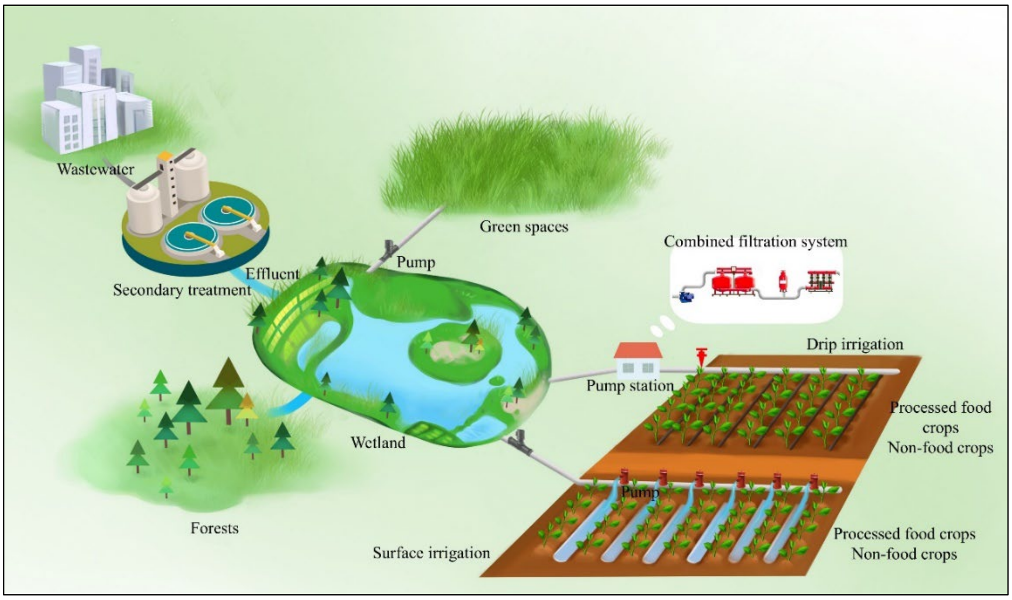


Figure 5.4. Sketch map of “WR” mode *(**Source**: Author's own elaboration)*

Under the DR mode (Figure 5.5), the effluent from secondary treatment plants is directly distributed to irrigation systems. To control health risks, surface irrigation and drip irrigation are recommended for processed food crops, non-food crops and forests.

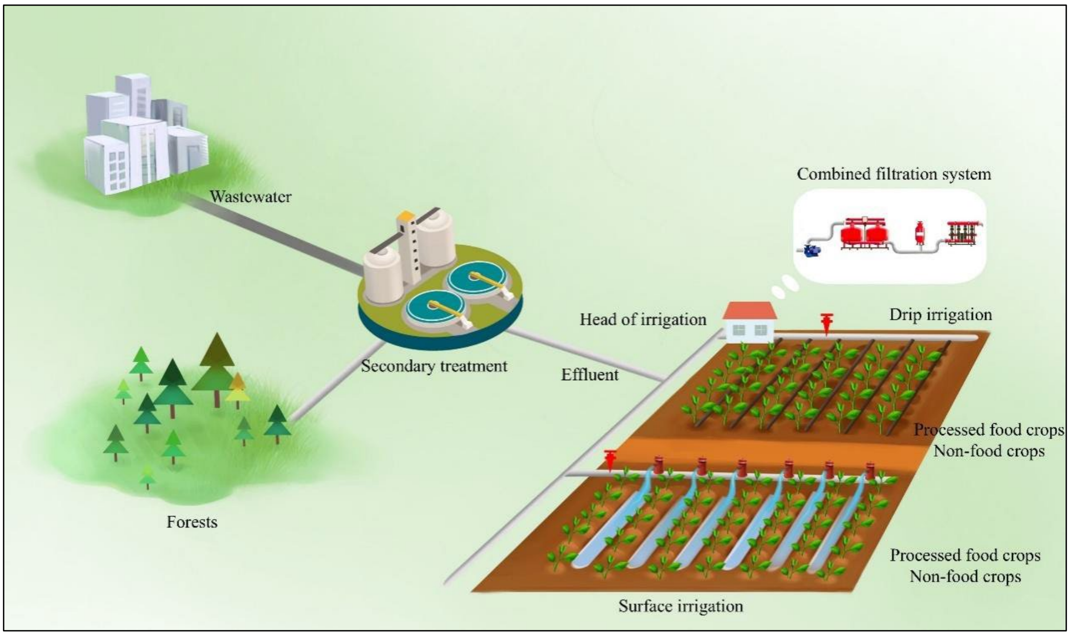


Figure 5.5. Sketch map of “DR” mode *(**Source**: Author's own elaboration)*

Under the TR mode (Figure 5.6), the effluent from tertiary treatment plants is directly distributed to irrigation systems. Tertiary treatment produces good quality effluent with lower health risks which suits all types of crops and irrigation methods.

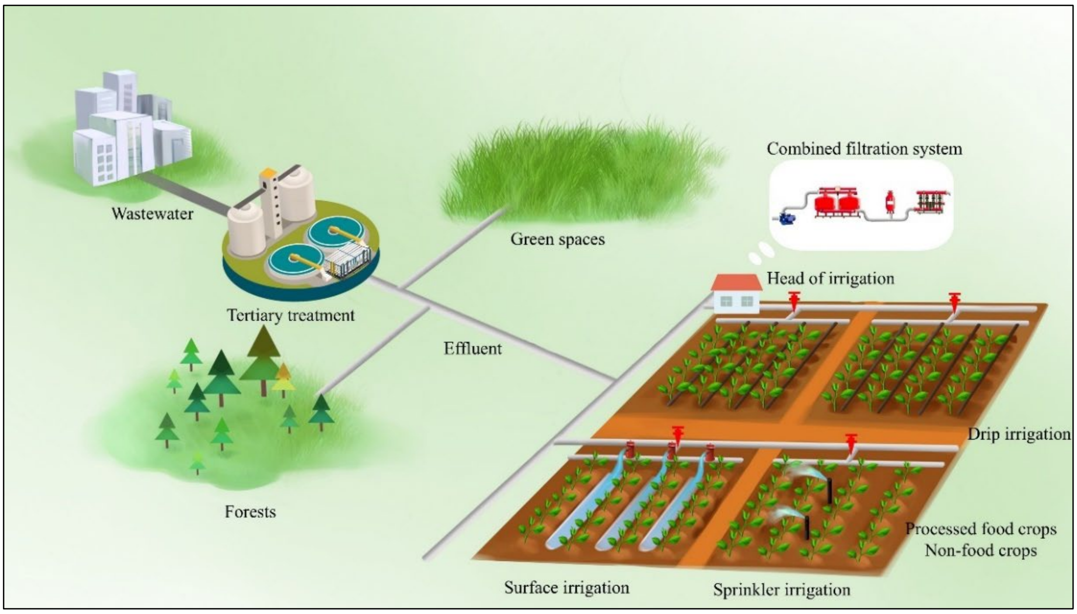


Figure 5.6. Sketch map of “TR” mode *(**Source**: Author's own elaboration)*

5.2 Design consideration for irrigation methods

5.2.1 Selection of irrigation methods

The regular irrigation methods can be classified into 3 groups: full surface irrigation, partial surface irrigation and subsurface irrigation according to spatial distribution and movement of irrigation water. Soil profile is fully wetted by irrigation water under gravity in full surface irrigation which includes border irrigation, furrow irrigation, flood irrigation and sprinkler irrigation. Soil profile is partially wetted by irrigation water under capillarity in partial surface irrigation which includes drip irrigation and micro sprinkler irrigation. Soil profile is partially wetted by irrigation water under capillarity in subsurface irrigation, which includes the method of subsurface drip irrigation.

Under fresh water irrigation, the selection of irrigation methods mainly depends on water application efficiency goal, crop type, cultural method, soil type, topography, investment, and the capacity of operation and management (Table 5.2). High water application efficiency is the priority objective of the selection of irrigation methods in water-stressed areas.

Table 5.2. Basic Features of Selected Irrigation Systems

Irrigation method	Topography	Crops	Comments and recommendations
Surface (flood) irrigation			
Widely spaced borders	Land slopes capable of being graded to less than 1% slope and preferably 0.2%	Alfalfa and other deep-rooted close-growing crops and orchards	The most desirable surface method for irrigating close-growing crops where topographical conditions are favorable. Even grade in the direction of irrigation is required on flat land and is desirable but not essential on slopes of more than 0.5%. Not suitable for sandy soils. Can be useful for salinity control purposes. *Water application efficiency 45-60%.*
Graded contour furrows	Variable land slopes of 2-25%, but preferably less	Row crops and fruit	Especially adapted to row crops on steep land, though hazardous due to possible erosion from heavy rainfall. Unsuitable for rodent- infested fields or soils that crack excessively. Actual grade in the direction of irrigation 0.5-1.5%. Ensure better health protection than border irrigation and can be useful fbr salinity control. *Water application efficiency 50—65%.*
Rectangular checks (levees)	Land slopes capable of being graded so single or multiple tree basins will be leveled within 6 cm	Orchards	Especially adapted to soils those have either a relatively high or low water intake rate. May require considerable grading. *Water application efficiency 30-60%.*
Sprinkler irrigation			
Center pivot Lateral move Hand-move Solid set, etc.	Undulating 1-> 35% slope	All crops, well suited for turf grass	Allows uniform, efficient and frequent application, as well as addition of chemicals and fertilizers. Good for rough or very sandy lands in areas of high production and good markets. Good method where power costs are low. May be the only practical method in areas of steep or rough topography. Good for high rainfall areas where only a small supplementary water supply is needed. High degree of automation. Capital costs typically 50 to 100% higher than surface irrigation, as well as operation and maintenance (O&M) costs. Affected by wind. High evaporation losses. *Water application efficiency 60—85%.*
Micro irrigation			
Microsprinkler irrigation	Wide range of terrain conditions	All crops	Point source application by a small spray on the soil surface, usually without overlapping. High efficiency and possibility of addition of chemicals. Especially suited for irrigation with recycled water enabling high-frequency and low-volume irrigation with easy scale up for small units. Capital costs typically over 100% higher than sprinkler irrigation, as well as O&M costs (+50%). *Water application efficiency 70—90%.*

Irrigation method	Topography	Crops	Comments and recommendations
Drip/trickle irrigation	Any topographic condition suitable for row crop farming	Row crops, fruits or vineyards	Perforated pipe on the soil surface drips water at base of individual vegetable plants or around fruit trees. High efficiency and possibility of addition of chemicals. Has been successfully used with saline irrigation water. Capital costs similar to mini-sprinkler irrigation and typically over 300-400% higher than surface irrigation. *Water application efficiency 70-95%.*
Subsurface irrigation	Field slope is limiting, in particular undulating terrain	Fruit trees, perennial row crops	Application of water below the soil surface through emitters or porous tube with discharge rates similar to drip irrigation. This system provides the highest health protection when using recycled water for irrigation. The main constraints are the high capital costs and needs of good design, operation and maintenance. *Water application efficiency 70-98%.*

Source:

- *FAO, 1992. Food and Agriculture Organization of the United Nations, Irrigation and Drainage Paper 47, Wastewater Treatment and Use in Agriculture, by Pescod, M..*
- *FAO, 2000. Food and Agriculture Organization of the United Nations, User's Manual for Irrigation with Treated Wastewater, FAO Regional Office for the Near East, Cairo, Egypt.*

Under reclaimed water irrigation, control of toxicity hazards and potential environmental impacts have to be considered when selecting irrigation methods. The health risk of reclaimed water irrigation originates from contact with reclaimed water, inhale of aerosol, and intake of irrigated agricultural products. Therefore, the selection of an appropriate irrigation method can help reduce the health and ecological risks. Feasible irrigation methods need to be helpful in controlling health risks and environmental contamination. Drip irrigation is recommended as the best irrigation method for its small direct impact on aerosol, soil, plant and groundwater. Surface irrigation is advisable for its small impact on aerosol. Sprinkler irrigation is not recommended due to the high risk of exposure to aerosol, and it can only be applied where nobody has access to when the irrigation system is operating (Table 5.3).

Table 5.3. Feasibility Evaluation of Regular Irrigation Methods for the Use of Reclaimed Water

Parameter of evaluation	Surface Irrigation	Sprinkler irrigation	Drip irrigation
Risk control of aerosol contamination	Medium to Good; Evaporation from irrigation water may cause slight aerosol contamination in a limited space [b]	Poor to fair; irrigation water may cause heavy aerosol contamination in a large space [c]	Good to excellent; irrigation water may have little impacts on aerosol [a]
Risk control of soil contamination	Fair to medium; Higher irrigation quota and lower water application efficiency may lead to hazards accumulation in soil [b]	Medium to Good; irrigation water may lead to a little impact on soil[b]	Good to excellent; lowest impact on soil compared to other irrigation methods [a]
Risk control of plant growth or products intake	Medium to Good; health risk may increase because of hazards transfer from soil to crops [b]	Fair to medium; leaves contacting with irrigation water may impact crop growth and lead to contamination of harvest fruits [c]	Good to excellent; little impact on plant growth or products intake [a]
Risk control of groundwater contamination	Fair to medium; high leaching may lead to groundwater contamination; such impact can be neglected regarding a dose of more than 8 m[c]	Medium to Good; Little impact on groundwater [a]	Good to excellent; little impact on groundwater [a]
Cost of equipment, operation and maintenance	Good to excellent; Low costs; lower technical requirement; easy maintenance [a]	Very high cost of equipment, significant O & M costs, and need for periodic maintenance [b]	High cost of equipment, moderate O&M costs, and need for maintenance [b]

Note: [a] Irrigation method is recommended as the priority choice; [b] Irrigation method is recommended;
[c] Irrigation method is not recommended; (***Source****: Author's own elaboration)*

5.2.2 Design Considerations for Drip Irrigation

Drip irrigation is a priority choice of irrigation method for reclaimed water irrigation thanks to its higher water use efficiency and smaller risk of aerosol contamination. However, the narrow flow path of emitters is vulnerable to clogging of suspended solids, chemical and biological factors (Li et al., 2015), which is a major problem of drip irrigation. The three aspects of filtration system, anti-clogging emitters and back-flush pipe systems should be considered in design to eliminate clogging risks (figure 5.7).

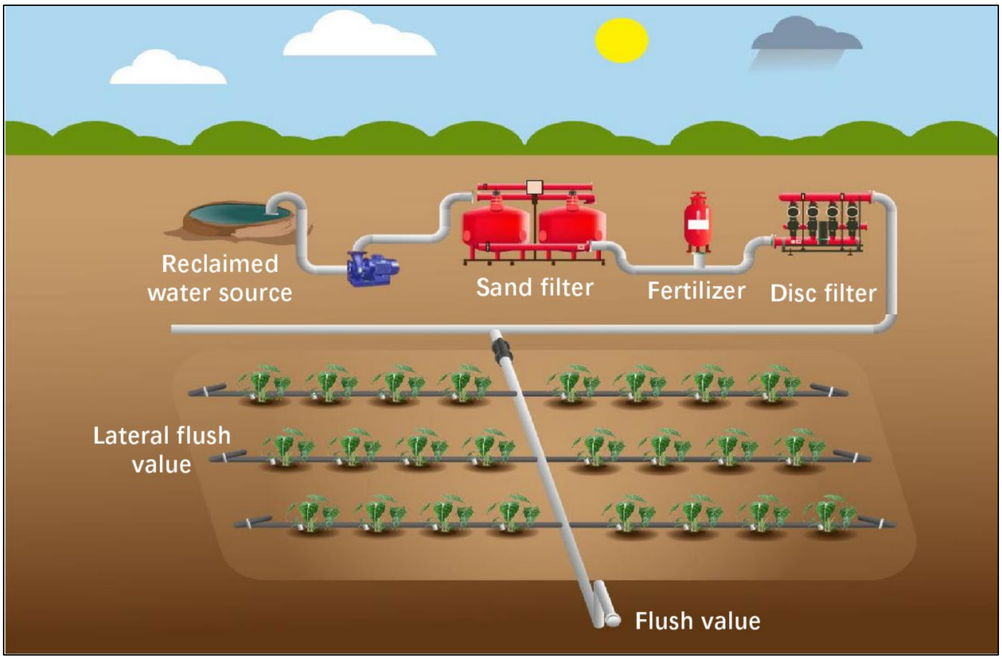
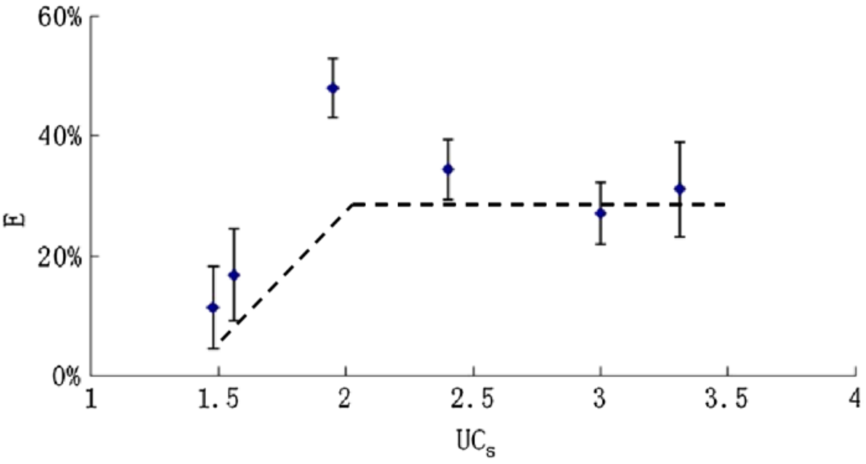
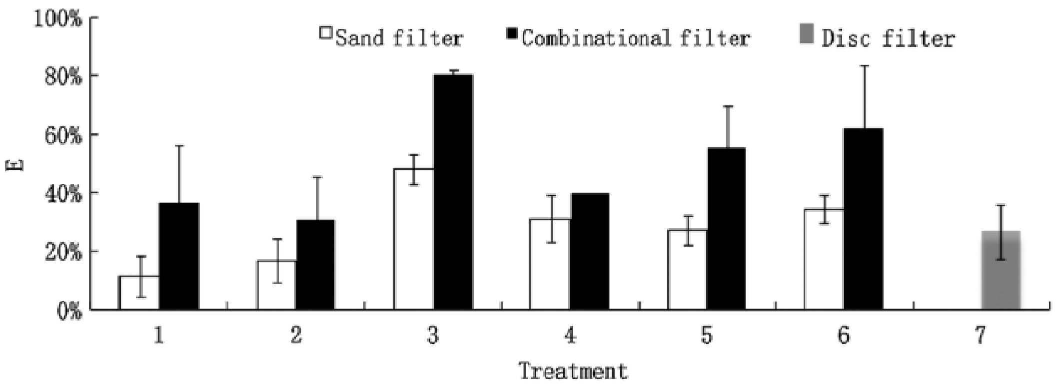


Figure 5.7. Anti-clogging drip irrigation system (***Source**: Author's own elaboration)*

Firstly, the Total Suspended Solids (TDS) in reclaimed water commonly ranges from 0 to 30 mg/L. It is necessary to establish two-stage filtration of sand filters and disc filters (or screen filters) to remove TDS in irrigation head. The Sand Uniformity Coefficient (UCs) is an important parameter for sand filters. It is suggested that UCs of 2.0-2.5 are defined as higher removal efficiency, under which 30%-50% of TDS are effectively removed (Figure 5.8a). Disc or screen filters should not be less than 120 meshes, and the removal efficiency of combinational filtration system could reach up to 80% (Figure 5.8b).



(a)



(b)

Figure 5.8. Filtration efficiency of different filters

(a. Regression between the sand infiltration efficiency (E) and the sand Uniformity Coefficient (UCs); b. The removal efficiencies of different filter systems) ***Source***: *Author's own elaboration.*

Secondly, around 20% of TDS are discharged into pipe systems after filtration, which lead to emitter clogging risks in conjunction with chemical and biological processes. Biofilm grows in emitter flow paths and reduces discharge (Figure 5.9). The smaller the cross-sectional area of the emitter, the smaller the clogging hazard (Figure 5.10). The shorter the flow path, the smaller the clogging hazard (Figure 5.11). Larger cross-section area means lower velocities, which will result in deposition in flow paths. Clogging tends to be less severe in inlaid labyrinth emitters than in column labyrinth emitters and on-line orifice emitters. Drip irrigation systems should adopt inlaid labyrinth emitters with short flow paths and feasible cross-section areas to prevent clogging.

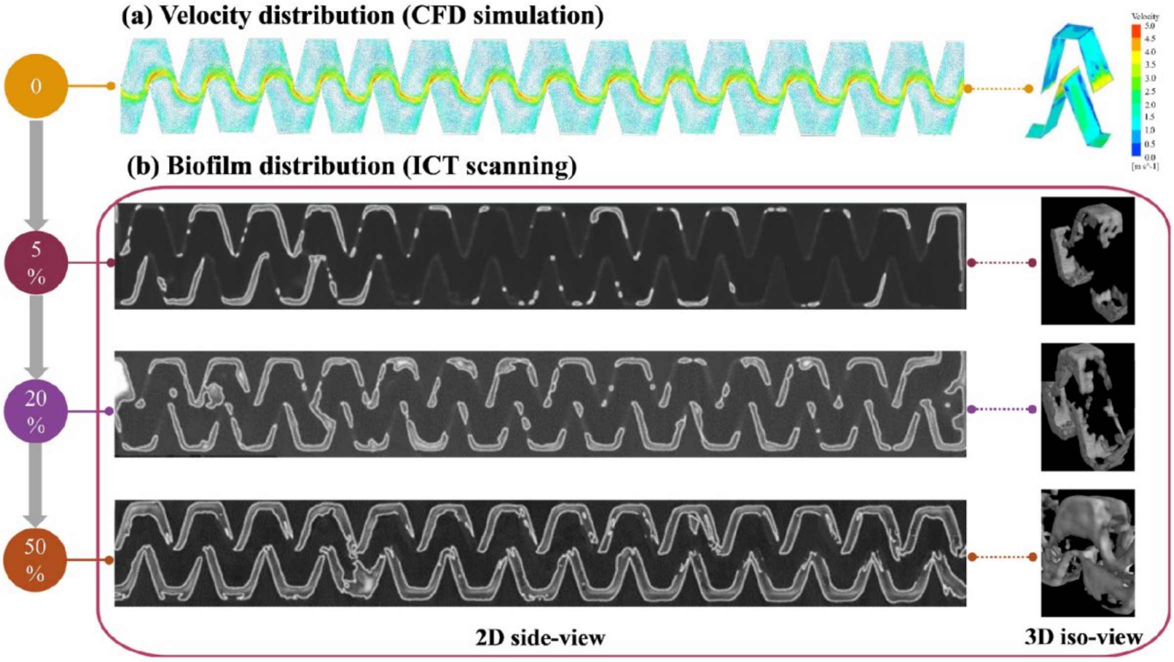


Figure 5.9. Local hydrodynamic and visible distribution of biofilms in the CFPs. In Fig. 3, 0, 5%, 20%, and 50% were the clogging degrees of the CFPs (Zhou et al., 2021)

Source: *Zhou, B., Hou, P., Xiao, Y., Song, P., Xie, E., Li, Y.K.*, 2021.Visualizing, quantifying, and controlling local hydrodynamic effects on biofilm accumulation in complex flow paths, Journal of Hazardous Materials, 462: 125937.*

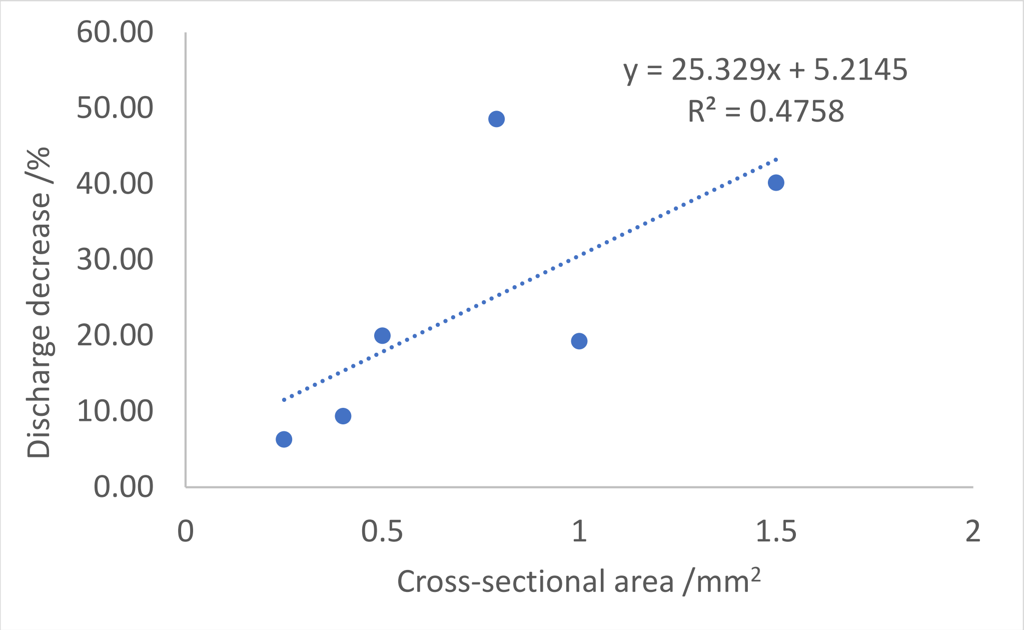


Figure 5.10. Relationship between discharge decrease and cross-sectional areas of flow path *(**Source**: Author's own elaboration)*

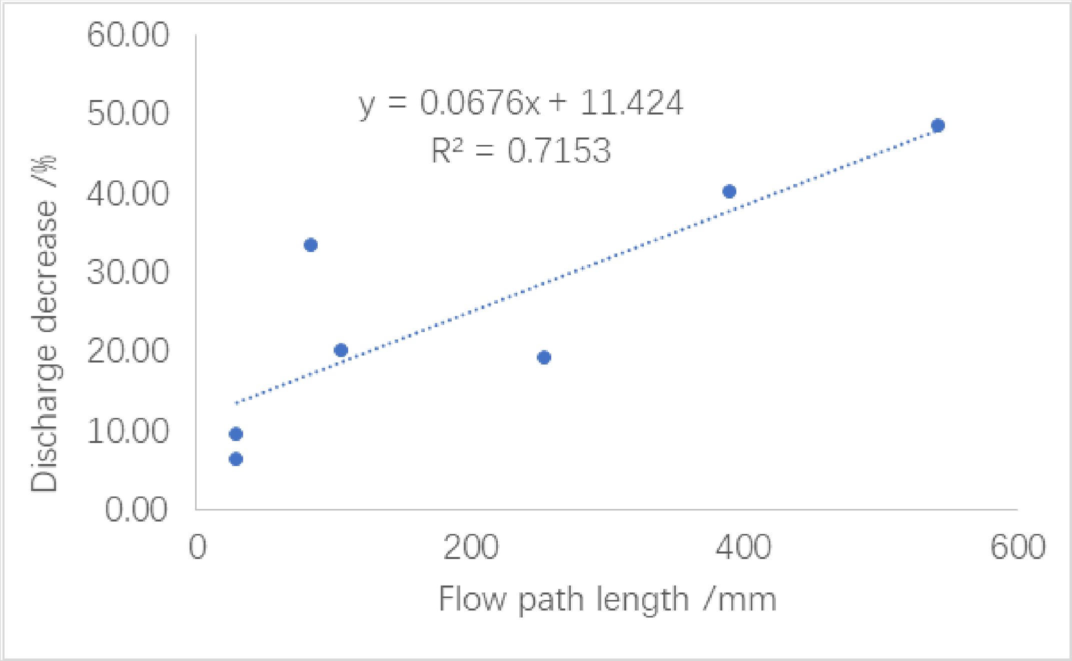


Figure 5.11. Relationship between discharge variations and flow path lengths *(**Source**: Author's own elaboration.)*

The deposition of TDS and biofilm accumulation inside pipes lead to clogging of lateral pipes and emitters. It is important to flush the deposition frequently. Therefore, the back-flush system should be added to the design to flush sediments out of pipelines. The back-flush system includes return pipes connected with laterals, flushing valves and automatic flushing controller. The controller can be set in a way that it can open the valves frequently according to management requirements.

5.2.3 Design Considerations for Surface Irrigation

In a surface irrigation system, water runs by gravity across the irrigated area. It is characterized by low cost and simple operation. Surface irrigation is a feasible method for reclaimed water irrigation since it creates less risk of aerosol exposure (compared with sprinkler irrigation). This method is suitable for soils of medium to fine quality. Border irrigation and furrow irrigation are the most widely used surface irrigation methods.

The design of surface irrigation systems should be based on local realities and relevant research findings. When calculating the designed flow capacity of the delivery system, it is important to measure seepage losses from unlined channels. In the case of large quantities of suspended solids in effluents, biofilm growth and deposition of suspended solids may affect seepage.

In border irrigation systems, the irrigated area is divided into long wide borders (usually 10-20m wide). The available discharge of a border irrigation system is higher than 100 m^3/h. Effluent flows from the distribution canals into each border through a pipe or gate valve. Therefore, it is very important to level the land to improve surface irrigation quality (Walker, 1989). This system can lead to contamination of vegetable crops, herbaceous fruit and root crops growing near the ground (Lazarova and Bahri, 2005).

Furrow irrigation does not wet the entire soil surface of shallow, narrow, gently sloping furrows, and is suitable in cases of small water discharge. Water is usually applied by gates and pipes, and the water infiltrates into the soil profile and spreads laterally to provide the desired wetting of the soil. The crops are grown on raised beds along the furrows. Furrow irrigation is well suitable for row crops irrigated with effluents (Feigin et al., 1991). Furrow irrigation can help reduce crop contamination because plants on the ridges are not in contact with effluents.

For detailed information on surface irrigation methods, refer to Walker and Skogerboe (1987).

5.2.4 Design Considerations for Sprinkler Irrigation

Sprinkler irrigation creates artificial rainfall, which may generate contaminated aerosols in operation. Therefore, an effluent sprinkler irrigation system should be designed in a way that the potential health risk of aerosols and windblown spray is minimized. Low sprinklers with low-pressure nozzles create less vertical spreading of effluents. In mechanically moved systems, the lateral can be installed with spray nozzles directed downward to apply the effluent close to the ground. It is also recommended to irrigate during periods of low wind velocity and during hours when people are least expected in the vicinity of the irrigated fields. Windbreakers and/or buffer zones should be allocated around the site (Feigin et al., 1991). It is also advisable to use effluents that have been effectively disinfected beforehand. It is necessary to spray fresh water shortly on the crop canopy before end when effluent quality may harm crop growth.

In sprinkler systems, especially the micro-spray systems, the effluent needs to be filtered to prevent nozzle orifices clogging. Sediments can accumulate in pipes, valves and nozzles. Combination of sand filters and disc or screen filters should be installed in sprinkler irrigation head. The diameter of a nozzle is suggested to be no less than 5mm (Lazarova and Bahri, 2005) to help reduce flow path clogging.

5.3 Water transportation and distribution

The selection of transportation and distribution system is based on investment and reuse objectives. Natural rivers could be used as main canals if effluents are needed to recover the river ecosystems at the same time. Lined canals are suitable for all distribution types, especially for high flowrate transportation. Pipes made of Polyvinylchloride (PVC), High Density Polyethyene (HDPE) and Low Density Polyethyene (LDPE), resistant to corrosion and the effects of chemical processes, can be used for different parts of main, submain and lateral canals. Steel and concrete pipes, easily corroded by high chloride and salt ions, are the least recommended. Steel and concrete pipes are more difficult to install compared with PVC, HDPE and LDPE pipes.

5.4 Storage requirements

Storage of effluents is key to the balance between water supply and demand, and higher water use efficiency of reclaimed water irrigation projects. The reclaimed water discharge from wastewater treatment plants is almost stable around the year while irrigation water requirements vary around the year. The mismatching of reclaimed water supply and irrigation water requirement will lead to low water application efficiency if there is no storage project. In most cases, storage means additional treatment which helps risk control and clogging prevention in micro irrigation and sprinkler irrigation systems. Based on the results of environmental impact assessment, existing projects such as reservoirs, lakes, and rivers or canals may be used as storage projects. If not, new storage projects have to be planned.

Table 5.4. Feasibility evaluation of different transportation and distribution systems

Materials	Scope of application	Comments and recommendations
Natural rivers	Main canals	Treatment plants are usually located in urban areas or scattered around urban areas. The effluent discharged to rivers may help recover surface water ecosystems and lower the investments in distribution and storage at the same time
Lined canals	All distribution parts	Compared to pipe distribution systems, lined canals are more suitable for high flowrate effluent. Canals cover larger construction area compared to pipe distribution systems
Polyvinylchloride (PVC) pipes	Submains or laterals	PVC pipes have less internal friction than other pipes, and can withstand various operation pressures. They will deteriorate in sunlight, and should be buried underground to avoid damaging by farm machinery, etc.
High Density Polyethyene (HDPE) pipes	Mains and submains	HDPE pipes combine strength and hardness, and are used as mains and submains. Compared to steel pipes, this type of pipes is resistant to corrosion and the impact of chemical processes, lighter and cheaper, and easier to be connected together
Low Density Polyethyene (LDPE) pipes	Laterals	LDPE pipes have lower operation pressure, and are lighter and cheaper than HDPE and steel pipes. Resistant to corrosion and the impact of chemical processes and easier to be connected with PE joints, LDPE pipes are usually used as laterals.
Steel pipes	Mains	Steel pipes have the highest operation pressures and durable properties compared to other pipes. It faces risks of corrosion by the large amount of chloride and salt ions in reclaimed water. Steel pipes need more investments and are more difficult to install.
Concrete pipes	Mains	Concrete pipes are the least suitable for effluent transportation. They may suffer deterioration risks of chemical corrosion, microbial corrosion, etc. due to the high level of chloride and sulfuric acid in reclaimed water

***Source**: Author's own elaboration.*

There are two types of storage: short-term and long-term. Short-term storage is for daily regulation or one rotation irrigation cycle (ranging from 1-2 days to 1-2 weeks), and can be performed in rivers, ponds, reservoirs and so on. Long-term storage is for seasonal regulation (storing effluents in winter for irrigation in growing seasons), and can be performed in ponds, reservoirs and aquifers.

Table 5.5. Feasibility evaluation of different storage projects

Types	Water body	Comments and recommendations	
Surface storage	Rivers	Effluent may be stored in rivers using sluice gates, rubber dams or weirs, which in the meanwhile also helps recover river ecosystems. Self-purification capacity of rivers may help additional treatment	Short-term storage
	Ponds or reservoirs	Ponds or reservoirs are commonly used for effluent storage. Storage leads to effluent quality improvement or external contamination, which depends on inlet effluent quality and meteorology. And if necessary, chlorination is recommended before distribution.	Short-term or long-term storage
Underground storage	Aquifers	Soil Aquifer Treatment (SAT), highly efficient in removing contaminants, is used for further treatment of effluents from wastewater treatment plants and stored effluents in aquifers. The limitations of SAT are high investment, and the demand for land resources with adequate hydraulic properties, etc.	Long-term storage

***Source**: Author's own elaboration.*

For new storage projects within designed irrigation area A and water supply flow Q_s.

$$V = \frac{10A(1-F)\sum_{i=1}^{m} E_{ci}a_iT_i}{\eta(1-f)} - Q_sTt_d \qquad \text{(5.1)}$$

Where:

A — Designed irrigation area（hm^2）;

V — Net storage capacity（m^3）;

K — Storage coefficient;

T — Designed irrigation cycle(d）;

T_i — Designed irrigation cycle of crop ranked i（d）;

E_{ci} — Designed evapotranspiration of crop ranked i (mm/d);

a_i — Irrigation area percentage of crop ranked i, %;

m — Crop number;

t_d — Designed water supply hours (h/d);

Q_s — Designed water supply flow (m^3/h);

η — Irrigation water use efficiency;

The required field area to where reclaimed water is applied is determined using the following equation:

$$A = \frac{\eta(1-f)VK}{10(1-F)\sum_{i=1}^{m} E_{ci}a_iT_i} \qquad \text{(5.2)}$$

$$K = 1 + \frac{Q_sTt_d}{V} \qquad \text{(5.3)}$$

5.5 Exposure Control Considerations in Design

The potential impact of reclaimed water irrigation comes from direct contact between humans and the reclaimed water, crops, soil and aerosols in the irrigated areas. Reclaimed water irrigation projects, with storage, transmission and distribution, and field irrigation systems, usually cover large areas. The risk of exposure to contaminants varies at the different stages of reuse. Some risks come from direct contact with reclaimed water and aerosols in the storage and distribution processes. Some are from direct contact with reclaimed water and aerosols and the consumption of uncooked crop. The processes of aquifer storage, pipe distribution, and subsurface and drip irrigation create less exposure risks. Different onsite control measures lead to different levels of log reduction, as displayed in Table 5.6.

Table 5.6. Log reductions provided by onsite controls

Control measure	Log reduction in exposure to pathogens
Cooking or processing of crops (e.g. potatoes, wine grapes)	5-6
Peeling the produce before consumption	2
Drip irrigation	2
Drip irrigation of crops with no ground contact	4
Subsurface irrigation of above-ground crops	4
Withholding periods	0.5 per day (viruses and bacteria)

***Source**: Daryl Stevens, 2006. Growing crops with reclaimed wastewater, CSIRO publishing.*

Table 5.7 summarizes the exposure risks for humans in different irrigation scenarios, the recommended positions of warning signals, and Minimum Distance (MD) as buffer zone. Warning signals help remind workers, passers-by, operators, and consumers. MD setup helps prevent the inhale of aerosols in operation.

Reclaimed water irrigation projects may be close to parks, residential communities, etc. For wells, surface water bodies, and springs for residents and livestock, the MD (as the buffer zone) should be larger than 150m; for residential communities and crowded public spaces, it should be larger than 50m.

Table 5.7. Control measures of exposure risks in different reuse processes

Reuse processes	Types	Exposure risks	Warning Signals	Buffering Zone
Storage systems	Rivers	Exposure of management workers and passers-by	Set up at conspicuous places along rivers. No contact allowed	MD≥5
	Ponds or reservoirs	Exposure of management workers	Set up around ponds or reservoirs. No contact allowed	MD≥10
	Aquifers	Exposure of management workers for infiltration basins	Set up around infiltration basins. No contact allowed	MD≥10
Transmission and distribution systems	Rivers	Exposure of workers, and possibly of passers-by	Set up at conspicuous places along rivers. No contact allowed	MD≥5
	Canals	Exposure of management workers, and possibly of passers-by	Set up at conspicuous places alone canals. No contact allowed	MD≥5
	Pipes	No exposure risk	/	/
Irrigation systems	Border irrigation	Exposure of fields workers, crop handlers, and consumers	Set up at conspicuous places at the border of the field.	MD≥15
	Furrow irrigation	Exposure of fields workers, possibly of crop handlers, and consumers	Set up at conspicuous places alone field edges.	MD≥10
	Sprinkler irrigation	Exposure of fields workers, crop handlers, and consumers	Set up at conspicuous places alone field roads. No access allowed during operation	MD≥50
	Subsurface and drip irrigation	Exposure of consumers	Set up at conspicuous places at the border of the field.	/

***Source**: Author's own elaboration.*

Figure 5.12. Example of warning signs used around RWI districts *(**Source**: Author's own elaboration)*

The warning signs include “***RWI District”, “No Swimming”, “No Drinking”, “No Playing”, etc., as displayed in Figure 5.12. The background color of the warning signs should be brown and the letters/lines/phrases should be white. These RWI sign (top-left) should be set up in conspicuous places around storage, transmission and distribution systems, and irrigation areas, so that they can be easily seen. The color of pipes used for transmission of reclaimed water should be different from that of freshwater supply pipes and should be well marked so there is no confusion.

* * *

6. Management Considerations of Irrigation Systems

6.1 Irrigation system maintenance

Regular maintenance should be carried out for the systems of storage, transmission and distribution, and irrigation, as displayed in Table 6.1. Maintenance helps prevent clogging and improve irrigation efficiency. Inspections should be conducted along rivers for erosion damages, rodents that can cause piping and washouts, and excess vegetation. Metallic structures should be painted or applied with protective coating, and metallic gates should be lubricated and left partially open during winter (Feign et al., 1991). For SAT, tillage breaks the surface crusts and vegetation that form on the infiltration basin's surface (Grinshpan et al., 2021).

Table 6.1. Control measures of exposure risks in reuse processes

Reuse processes	Types	Maintenance
Storage systems	Rivers	Rivers should be inspected for erosion damage, rodents that can cause piping and washouts, and excess vegetation
	Ponds or reservoirs	Ponds or reservoirs need dredging to remove sediment deposits
	Aquifers	Tillage breaks the surface crusts and vegetation that form on the infiltration basin's surface, and periodic tillage of the infiltration basin also roughens the basin's surface, and thus affecting air entrapment
Transmission and distribution systems	Rivers	Rivers should be inspected for erosion damage, rodents that can cause piping and washouts and excess vegetation
	Canals	Canals should be inspected periodically for damages. They need dredging to remove sediment deposits
	Pipes	Pipes should be inspected periodically for leaks in operation, and flushed periodically to drain out deposits or suspended matter to prevent clogging at low outlets. Drain valves should be installed and opened during freezing climate
Irrigation methods	Border irrigation	Border system should be restored before next planting
	Furrow irrigation	Furrow system should be restored before next planting
	Sprinkler irrigation	Water meters should be installed to measure flow rate of sprinkler irrigation systems to monitor the clogging degree at a certain working pressure. The filtration system should be automatically cleaned by back wash according to the pressure difference between inlet and outlet
	Subsurface and drip irrigation	Water meters should be installed to measure flow rate of subsurface and drip irrigation systems to clarify the clogging degree at a certain working pressure. The filtration system should be automatically cleaned by back wash according to the pressure difference between inlet and outlet. The lateral pipes or driplines should be flushed to drain suspended solid and depositions periodically. Chlorination treatment should be applied in operation to prevent emitter clogging

***Source**: Author's own elaboration.*

Chlore is used to treat emitter clogging. The lower limit of residual chlorine concentration at pipe bottom should be larger than 0.5 mg/L. The upper limits of residual chlorine concentration at pipe bottom are listed in Table 6.2. The designed chlorine concentration should be no more than 20 mg/L. The duration of chlorination treatment should be within 1-2 hours.

Table 6.2. The limit values of residual chlorine concentration for different crops

Crops	Sensitive to chlore	residual chlorine concentration at pipe bottom (mg/L)
Lawn, flower, tobacco, etc.	High	1~3
Vegetables, melons, etc.	Media	2~4
Corns, cotton, oil, fruits, etc.	Low	5~8

***Source**: Author's own elaboration.*

6.2 Fertilizer Management

Reclaimed water is rich in nutrients. Reclaimed water irrigation not only saves fresh water, but also recycles nutrients. The typical concentrations of nutrients in effluent from conventional sewage treatment processes are nitrogen 50 (20-85) mg N/L, phosphorus 10 (4-15) mg P/L, and potassium 30 (10-35) mg/L (Lazarova & Bahri, 2005). Table 6.3 lists the load of nutrients with various quantities of reclaimed water applied.

Table 6.3. Load of nutrients with various quantities of irrigation water applied(kg/ha/year)

Irrigation water m^3/ha/year	Concentration of a nutrient in wastewater(mg/L)								
	5	10	15	20	25	30	35	40	50
1000	5	10	15	20	25	30	35	40	50
2000	10	20	30	40	50	60	70	80	100
3000	15	30	45	60	75	90	105	120	150
4000	20	40	60	80	100	120	140	160	200
5000	25	50	75	100	125	150	175	200	250
6000	30	60	90	120	150	180	210	240	300
7000	35	70	105	140	175	210	245	280	350
8000	40	80	120	160	200	240	280	320	400
9000	45	90	135	180	225	270	315	360	450
10000	50	100	150	200	250	300	350	400	500

***Source**: FAO Regional Office for the Near East, 2003, Users manual for irrigation with treated wastewater, Cairo.*

Nutrients required by crops for canopy formation and bearing are listed in Table 6.4. Some of the nutrients are supplied by soil, and some by fertilizers and reclaimed water.

Table 6.4. Nutrients required by selected crops for canopy formation and bearing (Adapted from Papadopoulos)

Crop		N	P	K	P_2O_5	K_2O
Potato	Canopy(kg/ha)	86	7	120	16	144
	Tubers(kg/ton)	3.20	0.54	4.50	1.24	5.40
Tomato	Canopy(kg/ha)	95	12	108	27	130
	Fruits (kg/ton)	1.80	0.17	3.13	0.38	3.75
Eggplant	Canopy(kg/ha)	105	13	113	30	135
	Fruits (kg/ton)	1.96	0.17	3.2	0.40	3.8
Pepper	Canopy(kg/ha)	90	6	90	14	108
	Fruits (kg/ton)	2.0	0.26	1.83	0.6	2.2
Strawberries	Canopy(kg/ha)	85	5	88	12	106
	Fruits (kg/ton)	1.1	0.22	1.53	0.5	1.84

Crop		N	P	K	P_2O_5	K_2O
Lettuce	**(kg/ha)**	115	14	160	32	192
Mango	Canopy(kg/ha)	70	6	108	14	130
	Fruits (kg/ton)	1.35	0.19	1.65	0.44	1.98
Banana	Canopy(kg/ha)	250	26	800	60	1000
	Fruits (kg/ton)	2.0	0.22	5.0	0.5	6.0
Citrus	Canopy(kg/ha)	85	8	90	18	108
	Fruits (kg/ton)	1.44	0.19	1.53	0.44	1.84

***Source**: FAO Regional Office for the Near East, 2003, Users manual for irrigation with treated wastewater, Cairo.*

Chemical analyses at various soil depths reveal the nutrients available in soil, as displayed in Table 6.5 (FAO, 2003). The volume of soil occupied by roots is determined by crop spacing and irrigation methods. The fractions of soil occupied by roots for row crops with drip irrigation or flat-planting with sprinkler irrigation reach 30%-40% and 85%-95% respectively. The potential nutrient uptake efficiencies of the same crop with different irrigation methods are given in Table 6.6.

Table 6.5. Available nutrients in soil (kg/ha) as revealed by chemical analyses at various soil depths

Soil depth (cm)	Soil chemical analysis (mg/kg)										
	10	20	30	40	50	60	70	80	90	100	150
10	12	24	36	48	60	72	84	96	108	120	180
20	24	48	72	96	120	144	168	192	216	240	360
30	36	72	108	144	180	216	252	288	324	360	540
40	48	96	144	192	240	288	336	384	432	480	720
50	60	120	180	240	300	360	420	480	540	600	900
60	72	144	216	288	360	432	504	576	648	720	1080
70	84	168	252	336	420	504	588	672	756	840	1260
80	96	192	288	384	480	576	672	768	864	960	1440
90	108	216	324	432	540	648	756	864	972	1080	1620
100	120	240	360	480	600	720	840	960	1080	1200	1800

Note: It is assumed that the soil bulk density is 1.2 (***Source**: FAO Regional Office for the Near East, 2003, Users manual for irrigation with treated wastewater, Cairo)*

Table 6.6. Nutrient (NPK) uptakes (%) as influenced by irrigation method

Irrigation system*	Nitrogen	Phosphorus	Potassium
Furrow	40-60	10-20	60-75
Sprinkler	60-70	15-25	70-80
Microirrigation	75-85	25-35	80-90

Note: The values are of well designed and operated irrigation systems.
***Source**: FAO, 1992. Food and Agriculture Organization of the United Nations, Irrigation and Drainage Paper 47,*

Wastewater Treatment and Use in Agriculture, by Pescod, M..

Nutrient requirement of N, P and K can be calculated based on target yield, the nutrient capacity of soil and wastewater, using Equation 6.1 (FAO, 2003).

$$NR=NY-(NS+NW)\times 100/ES \quad (6.1)$$

Where NR refers to nutrient requirement (kg/ha), NY refers to nutrients requirement for certain yield (kg/ha), NS refers to available nutrients in soil (kg/ha), NW refers to nutrient capacity of wastewater (kg/ha), ES refers to nutrient uptake efficiency of irrigation system (%).

6.3 Salinity Control

Reclaimed water generally has higher salinity compared to fresh water due to the salts added into urban or industrial water use. For domestic water use, typically about 300±100 mg/L of dissolved salts are added (Lazarova and Bahri, 2005). The suggested value of total dissolved solids (TDS) is less than about 600 mg/L in drinking water (WHO, 2022). Therefore, TDS in reclaimed water sourced from domestic drainage water is mostly less than 1000 mg/L, below the limits set by reclaimed water quality guidelines for irrigation (Table 2.2). Control measures are necessary for reclaimed water irrigation given the different situations of salinity risks.

High-salinity reclaimed water (TDS≥1000 mg/L) not only requires a suitable and effective irrigation and drainage system, but also requires an integrated approach to soil, water and crop management. Low nozzle sprayers/sprinklers which are below the canopy and close to the ground, and sub-surface emitters are recommended. Keeping the root zone at a higher moisture content prevents the plant from experiencing water stress in addition to salt stress. This does not necessarily suggest that irrigations should be more frequent but rather, that irrigations should be scheduled when the roots deplete only a fraction of the available water. Avoid prolonged soil wetting as this can induce disease. A change in crop type should be considered as soil salinity increases over time, with little chance for leaching by rainfall or freshwater application. Non-conventional crops should be considered when using high-salinity reclaimed water. In any cases of high-salinity reclaimed water applications, the least saline-tolerant element in the system is the determinant factor. Under the practiced water management, understanding the overall impacts and interactions with the environment is critical. Therefore, an ecosystems approach must be adopted that considers high-salinity reclaimed water irrigation impact on the ecosystem.

Leaching should only be considered when the salt concentration exceeds the plant tolerance limit. Leaching could be the result of unavoidable irrigation inefficiency, occasional rain, and seasonal application of fresh water. Excessive or routine leaching after every round of irrigation is not desirable since leaching also means loss of nutrients, wastes water and adds extra salt if the leaching water is saline.

When two sources of water, i.e., fresh water and high-saline reclaimed water, are available, use fresh water for irrigation at the beginning of the growing season since seedlings are sensitive to salinity, and apply the high-saline reclaimed water at later stage when the crop is less sensitive. This is a better practice than irrigating with the mix of the two types of water during the whole growing season.

The impact of using reclaimed water irrigation 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.

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 (Ragab, 2019). SALTMED model can be downloaded from the following links[1].

Also online course is available at the website[2]. Models can also be used in a non-conventional way to predict missing parameters and difficult-to-measure parameters (i.e. $\pi 50$, K_{cb} , K_c, photosynthesis efficiency, etc.), to predict climate change impact (CO_2, radiation, rainfall, temperature, etc.), to produce an experimental design such as the best crop rotation, tillage level, fertilizer management and scheduling, to estimate the crop water requirement and time to irrigate (scheduling), and to design a program for data collection.

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[1] http://icid-ciid.org/inner_page/41

[2] https://www.youtube.com/watch?v=JRMeUFzuBYU.

Land management is important when using high-saline reclaimed water for irrigation. Land preparation is key to uniform distribution of irrigation water, infiltration and better salinity control. Subsoiling, chiselling, and ploughing break up compaction and improve water infiltration and leaching. Special treatments such as deep ploughing, mixing sand with the soil layer, and adding organic matter, gypsum or green manure could improve soil permeability. Conservative tillage such as zero or minimum tillage has advantages as it reduces soil evaporation, increases water availability, lowers surface salinity, multiplies organic matters, prevents soil erosion, boosts nutrient availability, cuts agrochemical use, and saves labor and machinery.

Accurate estimation of irrigation water requirement is important because irrigating with excessive high-salinity reclaimed 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.

The spatial variability and soil heterogeneity make area-based measurements more representative. In-situ continuous measuring of both soil moisture and salinity at the same time is more accurate than laboratory methods.

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. Currently, there are sensors that measure both and are not expensive. Models produce soil salinity that is 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.

When irrigating with high-salinity reclaimed water, crop selection is an important management decision. Field crops are generally more tolerant to salinity than annual vegetable crops and many trees and vine crops are prone to damage by ions, such as sodium, chloride and boron. These sensitive perennials should, whenever possible, be xcluded from brackish water irrigation. The most desirable characteristics in selecting crops for irrigation with high-salinity reclaimed water are: 1) high marketability and economic value, 2) high tolerance to salts and specific ions, 3) ability to maintain production and quality under saline conditions, 4) low potential to accumulate trace elements in tissue, and 5) ease of management and compatibility within crop rotation. Examples of salt tolerance plants are, Salicornia, salt-tolerant cereals such as quinoa and amaranth, jatropha, Atriplex and cassava. Plants are classified as sensitive, slightly tolerant, tolerant, very tolerant, etc., and the salinity limits for each category is given in tables published by FAO and AWC. 2023.

6.4 Monitoring

6.4.1 Monitoring for management of health risks

For human health risks, validation monitoring is important because the log reductions assured by designers and manufacturers cannot be assumed to be valid. Validation monitoring should cover all processes of sewer catchment trade-waste controls, secondary treatment system, lagoon, media filtration plant, membrane plant, ultraviolet plant, chlorination plant, cross-connection control, accidental ingestion control, etc. Pathogens are usually monitored as part of validation, and microbial indicator of *Escherichia Coli,* Coliphages*, Clostridia and* Seeded organisms (Gleeson & Gray, 1997). Verification monitoring needs to assess compliance with water quality requirements as well as compliance with specific good practices, and Table 6.7 provides a summary of typical sampling frequencies and determinants (NWQMS, 2006).

Table 6.7. Typical sampling program for operational monitoring of health protection harriers and verification of health water quality targets

Typical parameter	Sampling frequency [a]						
	Continuous	Dally	Weekly	Monthly	Biannually	Annually	Biennially
Operational monitoring							
Disinfection system performance (low-exposure schemes)		√					
Disinfection system performance (intermediate-exposure and high-exposure schemes)	√						
Filtration system performance (low-exposure schemes)		√					
Filtration system performance (intermediate-exposure and high-exposure schemes)	√						
Settling system performance (low-exposure schemes)			√				
Settling system performance (intermediate-exposure schemes)		√					
Settling system performance (high-exposure schemes)	√						
Turbidity or suspended solids (low-exposure schemes)			√				
Turbidity or suspended solids (intermediate-exposure schemes)		√					
Turbidity or suspended solids (high-exposure schemes)	√						
BOD5(low- and intermediate-exposure schemes)				√			
BOD5(high-exposure schemes)			√				
Flow (low-exposure schemes)			√				
Flow (intermediate-exposure schemes)		√					
Flow (high-exposure schemes)	√						
Catchment-input controls (such as trade-waste agreements)						√	
End-user controls (low-exposure schemes)					√		
End-user controls (intermediate-exposure schemes)				√			
End-user controls (high-exposure schemes)			√				
Cross-connection hydraulic controls (low-exposure schemes)		√					
Cross-connection hydraulic controls (intermediate-exposure and high-exposure schemes)	√						
Cross-connection plumbing controls						√	
Verification monitoring							
Escherichia coli (small low-exposure schemes)				√			
E coli (all other schemes)			√				
Somatic coliphage (high-exposure schemes)			√				
Clostridial spores (high-exposure schemes)			√				
Adenovirus (high-exposure schemes)				√			
Cryptosporidium oocysts (all large. high-exposure schemes)				√			
Audit of calibration activities				√			
Audit of preventive maintenance activities						√	
Audit of operational monitoring activities				√			

Source*: NWQMS (National Water Quality Management Strategy), 2006. Australian Guideline for waste recycling: managing health and environmental risks (phase 1).*

6.4.2 Monitoring for management of environmental risks

Environmental monitoring requirements are decided by the size of the reclaimed water irrigation scheme and the level of risk being managed. The content of the monitoring program generally increases as the size of the system grows: larger system, larger risk of exposure for the environmental factors of soil, water, and plants. Baseline monitoring is essential to the establishment of a reclaimed water irrigation project. Environmental risks are often calculated and managed relative to the baseline rather using absolute guideline values. Validation monitoring can be used to evaluate whether the treatment processes meet the requirement of environmental target values. Verification monitoring targets include effluent water quality, soils, plants, terrestrial and aquatic biota, ground and surface water (NWQMS, 2006).

Table 6.8. Typical sampling program for verification monitoring of environmental water quality, soil, groundwater, surface water

Hazard		Sampling frequency[a]									
		Continuous	**Dally**	**Weekly**	**Monthy**	**Quarterly**	**Biannually**	**Annually**	**Biennially**	**Intense rain events**	**Algal bloom Risk high**
Reclaimed water											
Boron					√						
Cadmium					√						
Chlorine disinfection residuals		√									
Nitrogen (total)					√						
Nitrate					√						
Phosphorus(total)					√						
Salinity(electrical conductivity)		√									
Chloride					√						
Sodium					√						
Sodium adsorption ratio (SAR)					√						
Surfactants					√						
Endocrine disrupting chemicals					√						
Ammonia				√							
Aluminium				√							
Arsenic					√						
Copper					√						
Lead					√						
Mercury					√						
Nickel					√						
Zine					√						
Phenol					√						
Soil											
pH	0-10[b]						√				
	30-50[c]										
	90-100[d]										
Salinity(electrical conductivity)	0-10[b]						√				
	30-50[c]							√			
	90-100[d]							√			
Sodium adsorption ratio (SAR)(or exchange sodium percentage)	0-10[b]						√				
	30-50[c]						√				
	90-100[d]						√				
Cadmium	0-10[b]						√				
	30-50[c]										

Hazard		Sampling frequency^{a}									
		Continuous	Dally	Weekly	Monthy	Quarterly	Biannually	Annually	Biennially	Intense rain events	Algal bloom Risk high
	90-100^{d}										
Nitrogen (total)	0-10^{b}						√				
	30-50^{c}							√			
	90-100^{d}							√			
Phosphorus(available)	0-10^{b}						√				
	30-50^{c}							√			
	90-100^{d}							√			
Boron	0-10^{b}						√				
	30-50^{c}							√			
	90-100^{d}										
Groundwater											
Water level						√					
pH						√					
Salinity (electrical conductivity)						√					
Nitrogen (total)						√					
Nitrate						√					
Phosphorus (toral)						√					
Chloride						√					
Sodium								√			
Calcium								√			
Magnesium								√			
Bicarbonate								√			
Sodium adsorption ratio (SAR)								√			
Iron								√			
Aluminium								√			
Surface water											
pH						√				√	
Salinity (clectrical conductivity)						√					
Nitrogen (total)						√					
Phosphorus (total)						√				√	
Chlorophyll-a								√			√
Aluminium						√					

Source: *NWQMS (National Water Quality Management Strategy), 2006. Australian Guideline for waste recycling: managing health and environmental risks (phase 1).*

7. Conclusions

Safe reuse of reclaimed water is a global issue for SDG. In order to promote reclaimed water irrigation, these Guidelines are drafted based on an overview of international Guidelines, standards and new research findings. Technical requirements of water quality, plant classification, planning, design and management are summarized systematically to make it more helpful for decision makers, officials, engineers, and farm managers.

1. The water quality Guidelines and standards of different countries and international organizations that are related to reclaimed water irrigation have been reviewed. For the quality of reclaimed water, there are four groups of parameters: organic and nutrient parameters, inorganic parameters, heavy metal parameters, and hygiene and sensory parameters. Water quality requirements are proposed for A, B and C plant classes.

2. Health risk control is essential for the safe reuse of reclaimed water. Crops should be classified and selected according to the exposure risk for health. Among the proposed groupings of crops, class A refers to high-exposure-risk food crops consumed raw or unprocessed; class B includes processed food crops, fodder crops and green space with public easy access; class C covers nonfood crops and green space located in places of difficult or controlled public access.

3. Environmental risk control is an important issue in reclaimed water irrigation. Two methods are proposed to evaluate groundwater pollution risks for feasibility mapping under reclaimed water irrigation. A contamination risk model is established to evaluate the feasibility of irrigation area. In addition, multi-parameter method is used to evaluate groundwater vulnerability for feasible allocation of irrigation area. The engineering considerations are given for different allocations.

4. Reclaimed water irrigation projects should be planned systematically. Six general layout modes are proposed to ensure efficient and safe reuse. The technical requirements of design, water transportation and distribution, storage, and exposure control are given in details. Due to the difference between RWI and fresh water irrigation, the specifications of design are set in a way that meets the demand for contamination control and clogging prevention.

5. Efficient operation and management of an irrigation project can contribute to the safe reuse and risk control. The maintenance requirements are introduced for the whole process of water storage, transportation and distribution, and irrigation. Also discussed are the proper ways of calculating and managing input load of different fertilizers, taking fully into account the rich nutrients in reclaimed water. Monitoring frequencies and parameters should be considered to control health and environmental risks.

* * *

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