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WATER QUALITY IN AGRICULTURE: **Risks and risk mitigation**

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Abbreviations and acronyms

AM	Adaptive Management
ASC	Aquaculture Stewardship Council
BMPs	Best Management Practices
BOD	Biological Oxygen Demand
CAC	Codex Alimentarius Commission
CCC	Criterion Continuous Concentration
CCFH	Codex Committee on Food Hygiene
CEC	Contaminants of Emerging Concern
CMC	Criterion Maximum Concentration
CPO	Costs per Observation
CROSS	Cation Ratio of Structural Stability
DNR	Department of Natural Resources
DO	Dissolved Oxygen
DPSIR	Drivers, Pressures, State, Impact, Response
DSS	Decision Support Systems
DTs	Decision trees
EC	Electrical Conductivity
ECe	Electrical Conductivity of the extract of a saturated soil paste
ECt	ECe threshold of yield decline
ECw	Electrical Conductivity of irrigation water
EPA	Environmental Protection Agency
ESI	Electrochemical Stability Index
ESP	Exchangeable Sodium Percentage
ExNa	Exchangeable Sodium
FAO	Food and Agriculture Organization of the United Nations
FC	Field Capacity
GAP	Good Agricultural Practices
GEMS	Global Environment Monitoring System
GIS	Geographical Information Systems
GLAAS	Global Analysis and Assessment of Sanitation and Drinking-Water
HACCP	Hazard Analysis and Critical Control Point
ISO	International Organization for Standardization
IAA	Integrated Aquaculture-Agriculture
IWMI	International Water Management Institute
JMP	Joint Monitoring Programme
LEAP	Livestock Environmental Assessment and Performance Partnership

LDC	Low Developing Country
LR	Leaching Requirement
MCDA	Multi-Criteria Decision Analysis
MQW	Marginal Quality Water
NRMMC	National Resource Management Ministerial Council (Australia)
PES	Payments for Environmental Services
POPs	Persistent Organic Pollutants
PPCP	Pesticides, and Pharmaceuticals and Personal Care Products
QMRA	Quantitative Microbial Risk Assessment
RF	Rice-fish system
RM	Rice Monoculture
RMC	Recommended Maximum Concentrations
SAR	Sodium Adsorption Ratio
SDG	Sustainable Development Goals
SSP	Sanitation Safety Planning
STEC	Shiga toxin-producing *E. coli*
TDS	Total Dissolved Solids
TSS	Total Soluble Salts
TWW	Treated Wastewater
UNCITRAL	United Nations Commission on International Trade Law
UNEP	United Nations Environment Programme
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
WHO	World Health Organization
WGS	Whole-Genome-Sequencing
WLE	Water, Land and Ecosystems program
WSPs	Waste Stabilization Ponds

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Foreword

Water scarcity is one of the leading challenges for sustainable development as water is essential not only for humanity, but also foragricultural production, food security, and is the lifeblood of our ecosystems. Yet, our freshwater resources are dwindling at an alarming rate, accelerated by population growth and climate change.

An often-overlooked factor contributing to water scarcity is water quality deterioration, especially in many low- and middle-income countries where water treatment and other pollution control measures are not keeping pace with population growth and urbanization. This is resulting in about 30 million hectares of agricultural land, home to over 800 million residents, irrigated with unsafe water. Salinity is the other major factor affecting water quality. It is affecting globally 20% of the cultivated land area, and an estimated 33% of irrigated land.

Farmers facing related water quality challenges need guidance to understand the risks and options on how to address them, especially where conventional wastewater treatment is not yet available. The Food and Agriculture Organization of the United Nations (FAO) has been at the forefront of providing this support with its benchmark publication "Water Quality for Agriculture" (1976) and "Wastewater Treatment and Use in Agriculture" (1992). However, over the last 30 years, water quality challenges have significantly grown, resulting in a plethora of new research and information related to water pollution, risk assessments and risk mitigation, as well as various sets of new water reuse guidelines.

"Water Quality in Agriculture: Risks and Risk Mitigation" is providing the latest information on the water quality requirements of crop, livestock and fish farming, the assessment of water quality, and options to address any related challenges. It also provides guidance on good practices to avoid negative downstream impacts of agriculture on water quality.

Through partnership between FAO and the International Water Management Institute (IWMI), and supported by leading experts from around the globe, we are happy to present this new publication for use by farm and project managers, consultants, engineers, and the academic community to evaluate water quality data and identify applied solutions for a water-secure future.

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Chapter

1 Introduction

Sasha Koo-Oshima

Water supports important ecosystem services, functions as a non-substitutable input to crop and animal production, and is essential for sustaining economic growth, health and resilience of a country. However, water is also a finite resource and is becoming increasingly scarce in many parts of the world with more countries facing water stress due to climate change. Water pollution from domestic, industrial, and/or agricultural sources can severely affect the availability of the resource for various uses, as well as human and environmental health. Agriculture, as the largest single user of freshwater resources, is also a significant source of chemical and organic pollution to surface water and groundwater resources, causing human illnesses, loss of biodiversity, contamination of marine ecosystems from land-based activities, closure of drinking water sources due to nutrients and toxic algal blooms, and global contamination by persistent organic pesticides.

The 2030 Agenda for Sustainable Development acknowledges the significance of water quality[1], and policy makers have identified water reuse as key to a more sustainable future. This is particularly important for many low- and middle-income countries where wastewater treatment is not keeping pace with urbanization.

Growing urbanization is increasing the demand for water and producing more wastewater. Different sectors such as agriculture, industry and households will face stronger competition for scarce water resources. Achieving sustainable urban development, including food and water security, requires sustainable production and consumption patterns by incorporating water valuation into integrated water resources management and transforming food systems. Globally, about 330 km^3 of urban wastewater, 660 km^3 of industrial wastewater (including cooling water) and an estimated 1260 km^3 of agricultural drainage effluent are annually discharged untreated into the environment (Mateo-Sagasta, Zadeh & Turral, 2018), affecting about 29 million hectares of irrigated farm land (Thebo *et al.*, 2017). In contrast, treated wastewater is reused on only about 1 million hectares of irrigated land worldwide (Drechsel, Qadir & Galibourg, 2022). Besides irrigated crop production, animal husbandry and aquaculture production are also greatly affected by poor water quality, and are significant contributors to water pollution as well (Ongley, 1996; Mateo-Sagasta, Zadeh & Turral, 2018). 'Point' and 'non-point' sources of pollution arise from human activities where the pollutants either have a single point of entry into receiving watercourses or diffuse (multiple) sources where the pollutants are more difficult to trace, measure and control (Ongley, 1996). Salinization is an example of diffuse pollution affecting presently over 20% of the total global irrigated area (Singh, 2021) which prompted the FAO guidelines **Water Quality for Agriculture** (Ayers & Westcot, 1976, 1985). Increasing global attention to domestic wastewater and health was addressed in the FAO benchmark publication titled **Wastewater Treatment and Use in Agriculture** (Pescod, 1992), which presented a guide to the use of treated effluent for irrigation and aquaculture, and drew on the 1989 WHO Guidelines for Safe Wastewater Use in Agriculture (WHO, 1989).

During the subsequent 30 years, the challenge of water quality has grown significantly (Ongley, 1996; UNEP, 2016; WWAP, 2017; Mateo-Sagasta, Zadeh & Turral, 2018; FAO 2021), accelerated by increasing

[1] "Water quality" refers to the physical, chemical, biological and organoleptic (taste-related) properties of water (United Nations, 1997).

water scarcity, urbanization, and climate change. Attention to alternative or nonconventional water sources, including wastewater and desalinized water (UN-Water, 2020; Qadir *et al.*, 2022), resulted in a flurry of new research on water pollution, risk assessments, and water quality management for water conservation or resource recovery in the context of the water–food–energy–ecosystem nexus. Updated water reuse guidelines and fit-for-purpose treatment (e.g., WHO, FAO & UNEP, 2006; USEPA, 2012; FAO & AWC, 2023) to bring water from a particular source to the quality needed for the intended use are increasingly regarded as the most efficient water management approaches. These approaches have been successful as part of integrated water resources management strategies that address multiple sectoral needs and objectives (Qadir *et al.*, 2022). Wastewater treatment remains the safest precondition for reusing the increasing volume of urban water discharge, be it for agriculture, forestry or greening urban and peri-urban areas, in support of a transition from a linear to a more circular economy in the rural-urban interface (Koo-Oshima, 2023). Additionally, aquaculture-agriculture hybrid systems can use brackish and reclaimed water efficiently for fish farming, irrigation, cooling, and non-potable domestic purposes[2]. Finally, residuals from treatment can be conveyed to larger, centralized treatment facilities where energy and nutrients (e.g., phosphorus) can be recovered. In summary, various motivations, benefits, and actions for wastewater reuse should be considered, such as those given below, depending on the geography and local water quality regulations:

- Increasing water security and building resilience to climate change resilience while reducing the dependence on long-distance water transfers or imports.
- Addressing groundwater depletion and related impacts such as land subsidence and saltwater intrusion through targeted groundwater recharge.
- Protecting downstream users, aquatic ecosystems and environmental flows through prevention and control of pollution and promoting safe water reuse.
- Augmenting water supply for irrigated agriculture and food security while freeing up high-quality water for urban use (Drechsel, Qadir & Baumann, 2022).
- Responding to changing economics of the cost of water, energy, and other factors for long-term economic and environmental sustainability (Winpenny *et al.*, 2010).

Promoting a circular economy within the Water–Food–Energy–Ecosystem Nexus approach (Koo-Oshima & Gillet, 2022) is important for addressing climate change, loss of biodiversity, environmental degradation, water scarcity and pollution from any sector and source, impacting the lives and prosperity of countless people every day, and threatening the vital needs of future generations.[3]

Based on this context, in 2020, FAO, in partnership with the International Water Management Institute (IWMI), began production of a review of current water quality guidelines to update the previous FAO guidelines from 1976 (revised in 1985) and 1992 in view of salinity, wastewater use, and other water pollution challenges. The result is the here presented one-volume guidance for evaluating the suitability of water for crop irrigation, livestock, and fish production, as well as environmental protection.

This publication, **Water Quality in Agriculture: Risks and Risk Mitigation,** emphasizes technical solutions and good agricultural practices, including risk mitigation measures suitable for the contexts of differently resourced institutions working in rural as well as urban and peri-urban

[2] FAO Nonconventional water symposium: https://www.fao.org/land-water/events/ncwsymposium19/en/

[3] https://dushanbewaterprocess.org/wp-content/uploads/2022/06/2022-final-declaration-final-draft-0608-en-final-1.pdf

settings in low- and middle-income countries. With a focus on sustainability of the overall land use system, the guidelines also cover possible downstream impacts of farm-level decisions. As each country has a range of site-specific conditions related to climate, soil and water quality, crop type and variety, as well as management options, subnational adjustments to the presented guidelines are recommended.

Water Quality in Agriculture: Risks and Risk Mitigation, is intended for use by national and subnational governmental authorities, farm and project managers, extension officers, consultants and engineers to evaluate water quality data, and identify potential problems and solutions related to water quality. The presented guidelines will also be of value to the scientific research community and university students.

The chapters in this publication address the following topics:

Chapter 2 describes the linkages between water quality and achieving the United Nations Sustainable Development Goals, and the need for water quality monitoring. **Chapter 3** provides an overview of existing water quality guidelines and standards across the world, including those reliant on technological advances and stringent water quality monitoring, and others based on health-based targets, as recommended by WHO. **Chapter 4** is dedicated to pathogenic threats,[4] in particular from domestic wastewater, while the elaborated **Chapter 5** targets chemical risks with significant emphasis on salinity (see also FAO & AWC, 2023). The interlinkages between water quality and aquaculture and water quality and livestock production are described in **Chapters 6** and **7**, respectively. The importance of water quality for a healthy environment and ecology is explored in **Chapter 8**, and further extended to watersheds and river basin scales in **Chapter 9**, looking at the approaches used to analyze, monitor, and manage water quality, and possible downstream impacts in their larger geographical context. Finally, **Chapter 10** provides an overview of the most common and/or significant barriers and drivers of relevance for the adoption of water reuse guidelines and best practices within a given regulatory and institutional context with special attention to low- and middle-income countries.

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[4] For guidance on anti-microbial resistance, see FAO (2020).

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Chapter 2

Water quality and the Sustainable Development Goals

Sara Marjani Zadeh, Pay Drechsel and Francisco Pedrero Salcedo

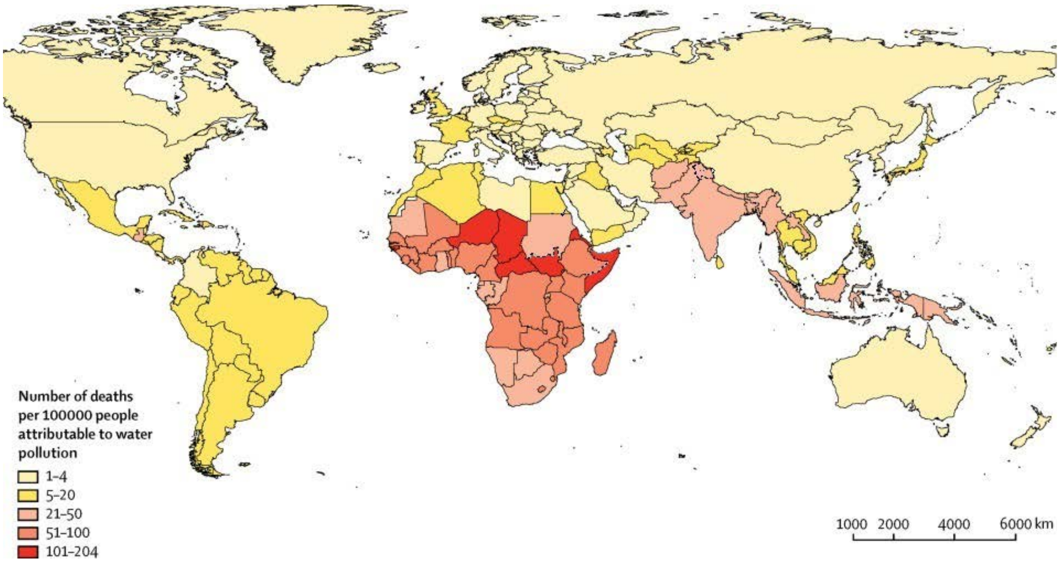
Pollution is the highest environmental cause of disease and premature death in the world today. According to the 2017 Lancet Commission on Pollution and Health, diseases caused by pollution were responsible for an estimated 9 million premature deaths in 2015 (i.e., 16 percent of all deaths worldwide) – three times more than deaths from AIDS, tuberculosis and malaria combined, and 15 times more than from all wars and other forms of violence. In the most severely affected countries, pollution-related disease is responsible for more than one death in four, and affects disproportionately the poor and the vulnerable. Health costs stemming from pollution-related disease are also responsible for up to 7 percent of health spending in middle-income countries which are heavily polluted and undergoing rapid development. Overall welfare losses due to pollution are estimated to amount to USD 4.6 trillion per year (Landrigan *et al.*, 2017).

Only surpassed by air pollution, water pollution presents the second highest risk, which resulted in an estimated 1.8 million deaths in 2015. Of these, 1.3 million are attributed to polluted water sources including drinking water, followed by unsafe sanitation (Landrigan *et al.*, 2017). The principal diseases linked to water pollution are acute and chronic gastrointestinal diseases, the most significant of which are diarrhoeal diseases (70 percent of deaths attributed to water pollution), typhoid fever (8 percent), paratyphoid fever (20 percent) and lower respiratory tract infections (2 percent) (GBD, 2015).

However, these estimates do not integrate illnesses and deaths from chemical contamination of water, including by pesticides, due to lack of data from most low-income and middle-income countries. Some of the most severe examples of biological and chemical pollution of drinking water are observed in rapidly urbanizing and industrializing lower-middle-income countries, where local waterways and groundwater are heavily polluted and no alternative water sources exist (Schwarzenbach *et al.*, 2010).

Population-based estimates of the number of deaths from water pollution are highest in sub-Saharan Africa (Figure 2.1). Large numbers of deaths have also been attributed to water pollution in some southeast Asian countries, although China has greatly reduced mortality from waterborne infectious diseases over the past two decades (GBD, 2015).

Figure 2.1. Number of deaths per 100 000 people due to water pollution, 2015



Source: Reproduced with permission from Landrigan, P.J., Fuller, R., Acosta, N.J.R., *et al.*, 2017. The Lancet Commission on pollution and health. The Lancet, 391 (10119): 462–512; modified to United Nations map geodata, version April 2023.

Notes: Final boundary between the Sudan and South Sudan has not yet been determined. Final status of the Abyei area is not yet determined. Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.

Water pollution also has effects on planetary health that extend beyond its impacts on human health. The pollution of rivers, lakes and oceans from agriculture, manufacturing and extractive industries can have catastrophic effects on freshwater and marine ecosystems that result in the collapse of fisheries and diminished livelihoods of local populations and others who rely upon fish as a major food source (WHO & CBD, 2015).

2.1 Agriculture as a cause and victim of water pollution

Over the past 100 years, increased population growth and shifts in anthropogenic activities have intensified agricultural production and expanded the industrial and urban sectors. These shifts have placed profound stress on ecosystems and natural resources, resulting in many regions in physical or economic water scarcity and water quality degradation. As the largest user of water resources, agriculture is both a cause and victim of water pollution.

2.1.1 Agricultural water pollution

Agricultural practices intensified at the start of the twentieth century, resulting in increased pollution due to heavy use of fertilizers and pesticides. Pesticide and fertilizer pollution are now among the most significant challenges to achieving safe water quality. According to FAO statistics, on average nearly 4 million tonnes of pesticides are used globally per year with China and the United States accounting for the highest levels of pesticide use at 1.4 million and 0.5 million tonnes per year, respectively. Globally, modelling has shown that agricultural insecticides may be entering surface waters in over 40 percent of land area (Ippolito *et al.*, 2015). In the United States, 90 percent of all water and fish sampled from streams across the country contained trace evidence of at least one chemical pesticide (Cassou, 2018). Pesticides are problematic in water because many of the chemicals used (aldrin, DDT, endosulfans and organochlorine insecticides) are persistent organic pollutants (POPs). In other words, they do not break down easily or rapidly but rather bioaccumulate in ecosystems.

Chemical fertilizer can be problematic when application exceeds plant need. Heavy fertilizer applications in China, and North and South America, for example, have produced adverse environmental consequences with increased nutrient loads in regional bodies of water, notably nitrogen and phosphorus, which are of particular concern. In the United States alone, the damage from eutrophication is estimated to cost almost USD 2.2 billion per year (Dodds *et al.*, 2009). A cross-country analysis showed that every additional milligram per litre of nitrate that enters the water increases stunting of children younger than 5 years by 11–19 percent and decreases adult earnings by 1–2 percent. This suggest that the marginal loss of health and productivity could outweigh the marginal gain in yields associated with an additional unit of fertilizer application (Damania *et al.*, 2019).

In addition to pesticide and fertilizer pollution, other agriculturally borne water quality challenges derive from animal husbandry and fishery effluent. These sources are responsible for depositing different assortments of antibiotics, pharmaceuticals, pathogens and nearly 700 other types of pollutants into the environment, contaminating groundwater, rivers, and surface and coastal waters (Mateo-Sagasta, Marjani Zadeh & Turral, 2017). Many of these pollutants are classified as emerging pollutants, which UNESCO describes as "any synthetic or naturally occurring chemical or any microorganism that is not commonly monitored or regulated in the environment with potentially known or suspected adverse ecological and human health effects" (UNESCO, n.d.). Scientists suspect that many of these pollutants are chronically and acutely toxic and carcinogenic, and disrupt endocrine function. The overuse of antibiotics is particularly problematic as this can lead to the emergence of antibiotic resistant microorganisms (Miranda, Godoy & Lee, 2018; Schar *et al.*, 2021).

2.1.2 Non-agricultural water pollution

Globally, between 50 percent and 80 percent of collected domestic and industrial wastewater is released without any prior treatment (Jones *et al.*, 2021; United Nations, 2017). An estimated 129 countries are currently not on track to achieving safe management of wastewater resources by 2030 (UN-Water, 2021), an issue that affects 35.9 million hectares of agricultural land that are directly and indirectly irrigated with wastewater (Thebo *et al.*, 2017). Municipal and industrial wastewaters contain similar pollutants as are found in agricultural run-off, but boast higher levels of pathogens aside from heavy, often toxic metals such as arsenic, lead or mercury. Pollution from industry and agriculture is also one of the most important ecosystem degraders, and in 2017 contributed to economic losses of over USD 579 million in China from damage to marine ecosystems alone (Song, Pan & Pan, 2020).

2.2 Water quality challenges and the Sustainable Development Goals

The 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDG) have concentrated global efforts to foster international collaboration. Global reporting mechanisms have been developed and are being implemented to monitor progress, also in view of water access and water quality.

The mission of SDG 6 is to ensure availability and sustainable management of water and sanitation for all. The specific targets for Goal 6 are listed below with sections referencing water quality in bold:

- 6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all;
- 6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations;
- 6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally;
- 6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity;
- 6.5 By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate;
- 6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.

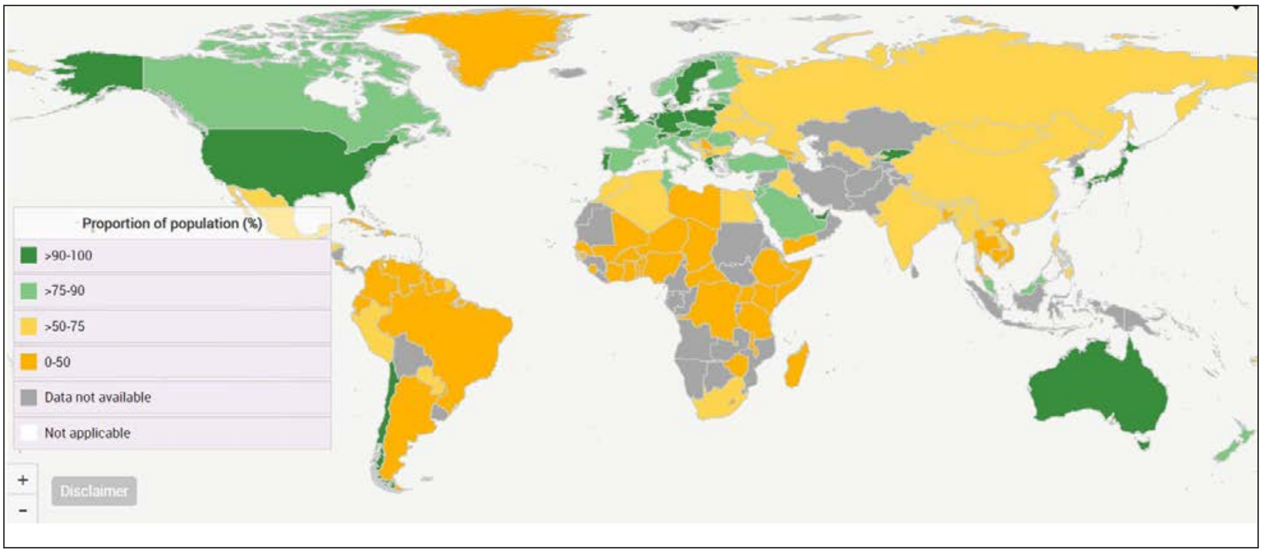
Several SDG 6 indicators are closely linked to water quality, with 6.3.1 and 6.3.2 having the greatest visibility:

- 6.2.1 Proportion of population using (a) safely managed sanitation services and (b) a hand-washing facility with soap and water;
- 6.3.1 Proportion of domestic and industrial wastewater flows safely treated ;
- 6.3.2 Proportion of bodies of water with good ambient water quality;
- 6.6.1 Proportion of water basins experiencing high surface water extent changes.

Safely managed sanitation (indicator 6.2.1a) is essential to protecting the health of individuals, communities and the environment. Open defecation, leaking latrines and raw wastewater can spread disease, provide a breeding ground for mosquitoes, and pollute groundwater and surface water that may serve as potential sources of drinking water (Damania *et al.*, 2019). Therefore, SDG 6.2 aims to achieve the universal provision of adequate sanitation and an end to open defecation. However, between 1990 and 2015, sanitation improvements accounted for just under 10 percent of the decline in child mortality (Headey and Palloni, 2019), and while some progress has been made, achieving this ambitious goal remains a fundamental challenge in many parts of the developing world (Figure 2.2).

SDG indicator 6.3.1 is an indirect water quality indicator monitoring the proportion of total, industrial and domestic wastewater flows safely treated in compliance with national or local standards (Figure 2.3). Wastewater collection and treatment help protect freshwater systems, the oceans and also human health, by preventing detrimental pathogens, nutrients and other types of pollution from entering the environment.

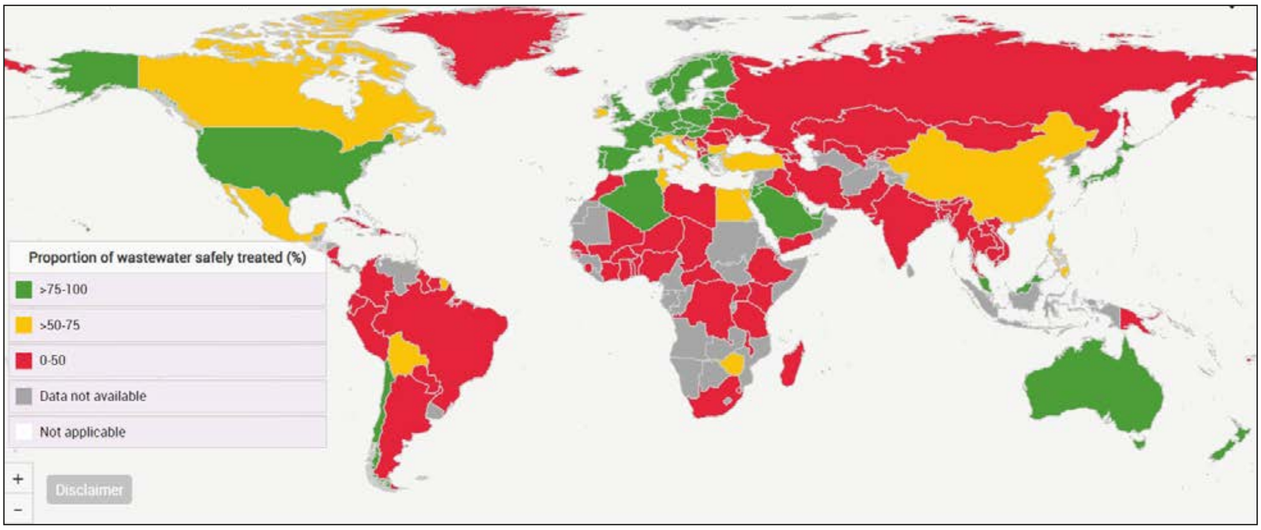
Figure 2.2. Proportion of population using safely managed sanitation services (indicator 6.2.1a), 2016-2022



Source: WHO, UNICEF. 2022. Progress on Sanitation (SDG target 6.2) Accessed 12 August 2023. https://sdg6data.org/indicator/6.2.1a.

Notes: Final boundary between the Sudan and South Sudan has not yet been determined. Final status of the Abyei area is not yet determined. Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.

Figure 2.3. Proportion of domestic wastewater flow (safely) treated (indicator 6.3.1), 2020-2022

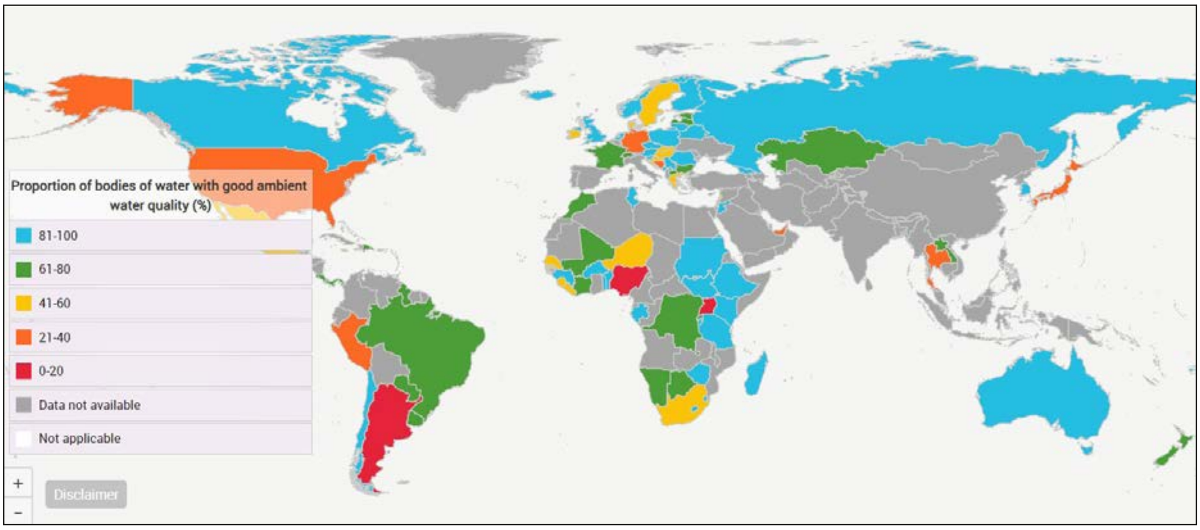


Source: WHO 2022. Progress on Wastewater Treatment (SDG target 6.3) Accessed 12 August 2023. https://sdg6data.org/indicator/6.3.1,

Notes: Final boundary between the Sudan and South Sudan has not yet been determined. Final status of the Abyei area is not yet determined. Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.

The second indicator directly related to water quality is 6.3.2. This refers to the percentage of monitored water bodies in a country classified as having good ambient water quality (Figure 2.4). The methodology uses a water quality index to classify water quality, which incorporates measurements of five core parameter groups: acidification, oxygen, nitrogen, phosphorus and salinity for surface water (rivers and lakes), and acidification, salinity and nitrogen for groundwater.

Figure 2.4. Level 1 proportion of bodies of water with good ambient water quality (indicator 6.3.2), 2017-2020



Source: UNEP 2020. Progress on Ambient Water Quality (SDG target 6.3). Accessed 12 August 2023. https://sdg6data.org/indicator/6.3.2,

Notes: Final boundary between the Sudan and South Sudan has not yet been determined. Final status of the Abyei area is not yet determined. Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.

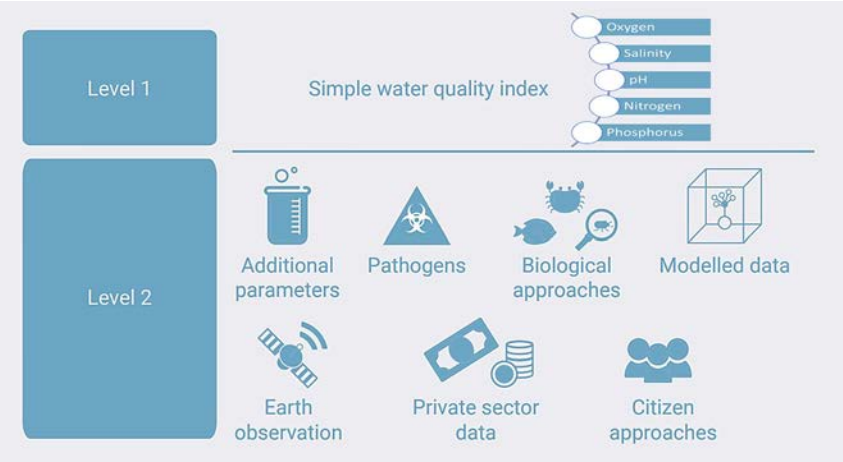
The methodology is based on samples collected or analyses performed in situ. Measured values are compared to target values that represent "good ambient water quality". These targets are set by countries at either the national, reporting basin district or water body level.

A threshold value of 80 percent compliance has been established to classify water bodies as of "good" quality. Therefore, a water body is classified as "good" if the measurements from the water body meet their targets at least 80 percent of the time, or "not good" if the targets are met less than 80 percent of the time. The overall national indicator score is based on water body type (river, lake or groundwater), and reporting basin district, which will consist of either a single large river basin or several smaller river basins (https://gemstat.org).

Indicator 6.3.2 differs from most other SDG 6 indicators due to its requirement for actual water sampling and (at a minimum) field laboratories. At its most basic (level 1 monitoring), the indicator uses methods that focus on the physicochemical characteristics of water that change in response to pressures of global relevance. These are nutrient enrichment, oxygen depletion, salinization and acidification. Indicator 6.3.2 thus complements 6.3.1, which describes the impact of poor wastewater treatment and the risk of pathogenic and chemical pollution.

There are many other water quality parameters which are routinely measured, like heavy metals or pesticides, as well as alternative monitoring approaches such as those that examine species that live in the water, and Earth observation techniques which rely on satellite imagery. These additional parameters and approaches are captured under Level 2 monitoring (Figure 2.5) which provides additional flexibility for countries to include further information that may be of national concern or relevance.

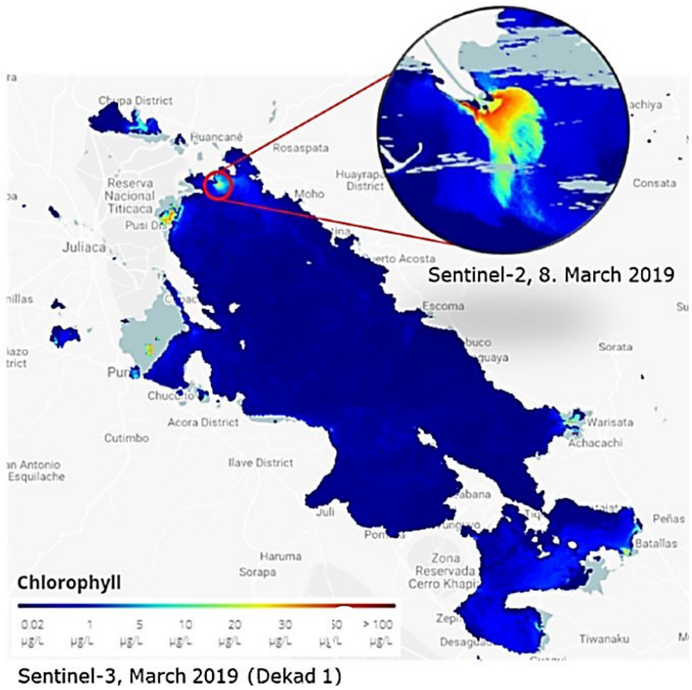
Figure 2.5. Examples of level 1 and 2 data sources for SDG 6.3.2. monitoring



Source:UNEP. 2021. Progress on ambient water quality. Tracking SDG 6 series: Global indicator 6.3.2 updates and acceleration needs. Nairobi, UNEP.

Advances in analysing satellite imagery have also enabled the creation of global datasets, for example on lake water quality, without need for local sampling (IOCCG, 2018). Although indicator 6.6.1 focuses on tracking spatial area changes over time in water-related ecosystems, the monitoring process also captures wherever possible water quality changes based on satellite data by measuring remotely two water parameters: turbidity and trophic state (UNEP, 2021b). Turbidity is a key indicator of water clarity and is influenced by the amount of suspended solids. The Trophic State Index shows the degree to which organic biomass accumulates in a water body and is most commonly used in relation to monitoring eutrophication. Remote sensing can assess water turbidity as well as chlorophyll-a concentrations in plants as a proxy for the trophic state, but cannot directly detect, for example, nutrient concentrations such as phosphorus and nitrogen. The potential for application is evident e.g. in the case of Lake Titicaca, where sewage water from nearby cities, industries and mines flows largely untreated into the lake (Figure 2.6). The nutrients in the wastewater support phytoplankton bloom events which the satellite can detect.

Figure 2.6. Elevated chlorophyll concentrations around the northern inlet of Lake Titicaca

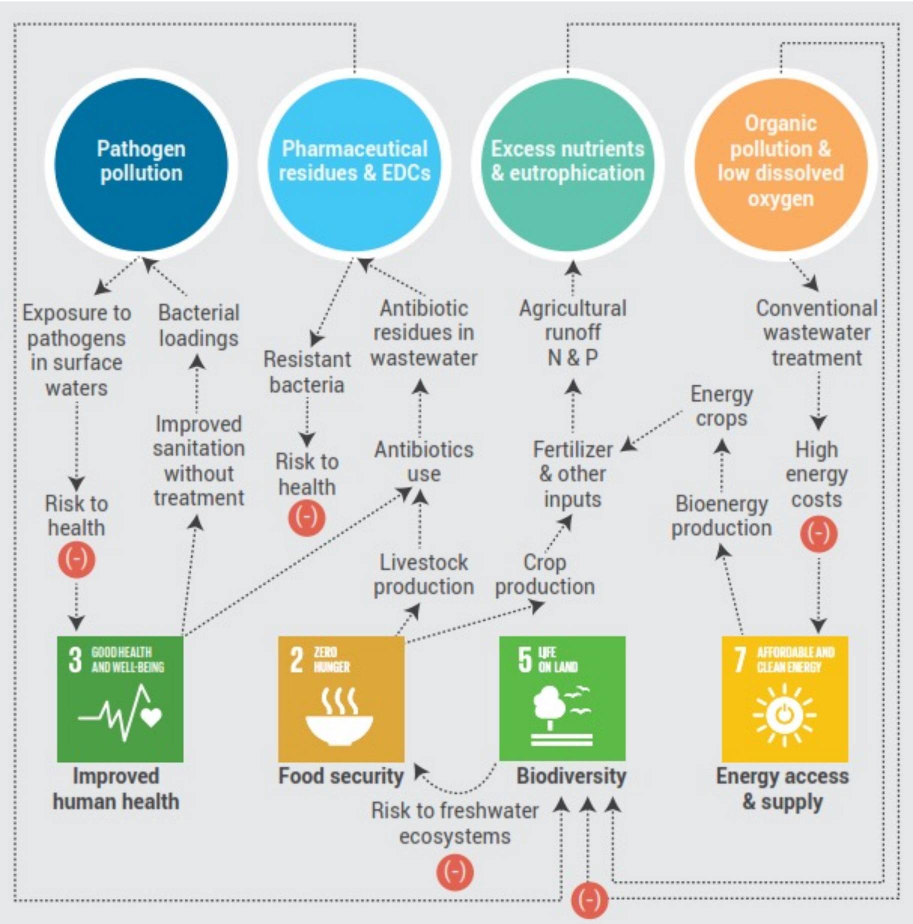


Source: UNEP 2021. Freshwater Ecosystems Analysis and Case Stories. Accesssed 12 August 2023. https://stories.sdg661.app/#/story/1/0.

Globally, the highest shares of impacted lakes are found in sub-Saharan Africa, Latin America and the Caribbean, Europe and Northern America, and Oceania, where more than 40 percent of lakes show signs of water quality deterioration relative to the 2006–2010 baseline (UNEP, 2016).

In addition to the specific SDG 6 targets, water quality will also have a profound influence on other SDGs. A recent UN-Water publication, Water and Sanitation Interlinkages across the 2030 Agenda for Sustainable Development, documents the pattern of reinforcing interlinkages between SDG 6 (including water quality target 6.3) and the other SDGs (UN-Water, 2016). For water quality, these include connections to targets related to increasing access to public services (SDG 1 and SDG 11), ending hunger (SDG 2), improving health (SDG 3), increasing access to energy (SDG 7), promoting sustainable tourism and industrialization (SDG 8 and SDG 9), and reducing marine pollution (SDG 14). Figure 2.7 illustrates some of these connections.

Figure 2.7. Water quality linkages with SDGs other than SDG 6



Source: UN-Water. 2016. Water and sanitation interlinkages across the 2030 Agenda for Sustainable Development. Geneva, UN-Water

2.3 Water quality monitoring

A significant challenge for establishing a global water quality database is limited monitoring and reporting capacity, especially in developing countries where the required financial resources, institutional capacities or analytical infrastructure are often lacking. The UN estimates that the absence of routine water quality data collection places over 3 billion people at risk, due to lack of information regarding the health of their freshwater ecosystems and, consequently, a lack of action to adequately address quality issues (UN-Water, 2021).

Through the UN-Water Integrated Monitoring Initiative for SDG 6 (IMI-SDG 6), the United Nations seeks to support countries in monitoring water- and sanitation-related issues within the framework of the 2030 Agenda for Sustainable Development, and in compiling country data to report on global progress towards SDG 6 (UN-Water, n.d.).

IMI-SDG 6 brings together UN organizations that are formally mandated to compile country data on the SDG 6 global indicators, and builds on ongoing efforts such as UNEP's Global Environment Monitoring System for Water (GEMS/Water), FAO's Global Information System on Water and Agriculture (AQUASTAT), the UN-Water Global Analysis and Assessment of Sanitation and Drinking-Water (GLAAS), and the WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP). There are currently four main approaches been employed to gather water quality data across countries (Damania *et al.*, 2019; UNEP, 2016):

- Efforts to grow the vast GEMStat database have proven vital for researchers and policymakers. The main limitation of the database, however, is that data are self-reported, and as a result, both the parameters employed and the frequency of collection are sporadic across and within countries. Coverage is particularly sparse in Africa, Central Asia, the Middle East, China, and southern and western South America.

- Remote sensing of water quality from satellite imagery or drones is a relatively new technique that is becoming more widespread and increasing in accuracy. Medium- to high-resolution and high-frequency satellites such as Envisat MERIS or Sentinel allow for Earth observations and data collection. Remotely sensed water quality data are limited, however, to certain parameters which demonstrate distinguishable changes in the spectrums observed by satellites (chlorophyll, total suspended solids, turbidity, floating vegetation, colourized dissolved organic matter and temperature). An important benefit is that the automatic capture of large water bodies by satellites eliminates the need for river or lake monitoring stations.

- When data from in situ observations or satellites are not available in the desired locations or at the required times, simulated data from hydrological models can be used. The factors that determine water quality are well known, and models that estimate risks of poor water quality at a global scale are gaining traction in the scientific and international community to fill existing gaps in available data (e.g. from GEMStat). Gaps can also be addressed through machine learning algorithms that can find patterns that would otherwise go undetected.

- Finally, citizen science and other crowdsourcing approaches may provide opportunities to simultaneously gather data and educate, engage and encourage public environmental compliance at different scales (Mistry, Borden & Lawson, 2016; UNEP, 2016). With the increasing availability of mobile phones and internet access in developing countries, citizen scientists can make a significant contribution to future water quality data collection, although recent evidence from a World Bank-supported project in Punjab, India, suggests that there are limits to this approach (World Bank, 2016, 2020).

According to UN-Water, current support mechanisms provided by the IMI-SDG 6 to engage countries and build their capacities are as follows:

- Written methodologies and guidelines for monitoring global indicators for use at the country level;
- Help desks, webinars and online tutorials;
- In-country technical assistance and training workshops for national, regional and global levels;
- Assistance with developing collaboration for cross-country learning and identification of good practices.

These mechanisms are helping countries to increase their access to existing water data, but require further efforts to generate new information. A wide array of technologies and methodologies are available for countries and communities to capture water quality data. Furthermore, modern chemistry methods and state-of-the-art monitoring technologies enable thousands of chemicals to be detected in water, even at extremely low concentrations (Zulkifli, Rahim & Lau, 2018). Fortunately, not everything needs to be tested for. While many parameters require state-of-the art lab facilities, a much smaller and more practical set of tests can provide a good sense of chemical or microbial water quality for monitoring purposes. Low-tech versions of tests are also available for situations where budgets are limited and/or citizen science approaches are targeted (Lawson & Mistry, 2017; Mistry & Lawson, 2018). This is important as not all countries have the analytical facilities or budgets for more specific and/or large-scale testing.

Choosing which technologies to install will thus depend on the selected parameters, the costs of sampling and analysis, the biophysical site conditions and infrastructure, and ease of use, among other factors. Although customizing and implementing more site-specific water quality monitoring is crucial, it is also imperative that the captured data are accurate, capture spatial and temporal variation, and are comparable between different data providers to enhance the reliability of the overarching database.

For the interpretation of data, organizations such as the World Health Organization (WHO), the European Commission and the US Environmental Protection Agency (EPA) have established "safe" concentration levels for common pollutants. However, there remains uncertainty about many "safe" values, largely due to the lack of well-established and locally valid dose-response functions that describe how these pollutants actually affect ecosystems, including human and animal health (Damania *et al.*, 2019).

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Chapter 3 Water quality guidelines in agricultural water use

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Agricultural use of reclaimed water has a long history and accounts for a significant percentage of the reclaimed water used globally. The use of reclaimed water for agriculture is also widely supported by regulatory and institutional policies. In addition, the World Health Organization (WHO, 1989, 2006) has provided guidelines to reduce risks where farmers use untreated and/or diluted wastewater either intentionally or unintentionally.

Historically, water reuse standards were first developed for agricultural water reuse (e.g. in California in 1918), with different countries subsequently developing different approaches to protect public health and the environment. A major factor in the choice of regulatory strategy in many countries is economics, specifically the costs of treatment, monitoring and distribution of the recycled water. Some developed countries have opted for developing conservative low-risk guidelines or standards based on relatively costly technology and stringent water quality monitoring (e.g. Australia, California, the European Commission and the USEPA). However, the feedback from practice and health risk assessments demonstrates that health risk mitigation can also be achieved by means of additional health protection barriers and the use of less expensive technologies, as recommended by the WHO (2006) guidelines.

Many water reuse standards and guidelines are developed with farmer and consumer health protection in mind. Contact, inhalation and, in particular, ingestion of reclaimed water containing pathogenic microorganisms or toxic chemicals, can create the potential for adverse health effects in humans and animals. The most common health concern associated with non-potable wastewater reuse is the potential transmission of infectious disease by microbial pathogens. Waterborne disease outbreaks of epidemic proportions have been controlled to a large extent where treatment has gained good household coverage, but the potential for disease transmission through the water delivery system has not been eliminated. With a few exceptions, there are minimal health concerns associated with chemical constituents where reclaimed water is not intended to be consumed (Lazarova & Bahri, 2005).

3.1. Key water quality parameters for agricultural water reuse

The most common risks and adverse impacts of water quality in water reuse systems are summarized in Table 3.1. The major water quality parameters and compounds of concern are given with the associated risk category and potential adverse impacts, as well as the type of regulatory tools and guidelines available.

The presence of pathogens is the main health concern when (reclaimed) water is used for irrigation. Because it is not possible to monitor all pathogens and their viability, coliforms are successfully used as microbial indicators (Asano *et al.*, 2007). Thermo-tolerant (faecal) coliforms are the most common microbial indicator, as well as *Escherichia coli* (*E. coli*), the most common faecal coliform. In developed countries, one of the major human health concerns related to water reuse is intestinal parasitic infections (WHO, 2006), which has led to the use of helminth eggs or spores of sulfate-reducing bacteria as another indicator.

Table 3.1. Water quality criteria for agricultural water reuse

Main objective for risk mitigation	Parameters of concern	Major parameters and compounds of concern	Main risks and adverse impacts	Type of regulatory tools and recommendations
Human and animal health protection and mitigation of health risks	Microbial parameters	Bacteria, viruses and protozoa Coliforms (total, faecal or *E. coli*) are the most common microbial indicator	Short-term microbial risk of infection	Major topic in water reuse regulations, guidelines and standards
	Chemical compounds	Heavy metals, organic micropollutants (pesticides, pharmaceuticals and health care products, endocrine disruptors, etc.)	Long-term biological risk of toxicity	Emerging issue Ongoing research
Environmental protection	Microbial and chemical compounds	Nitrate (groundwater), nitrate and phosphorus (eutrophication), residual chlorine (surface water), inorganic and organic micropollutants (soil and water resources)	Aquifer, surface water and soil pollution, Adverse impacts on biodiversity (flora and fauna)	Included in some wastewater treatment and reuse regulations and standards
Mitigation of agronomic impacts	Agronomic parameters and chemical compounds	SAR*, salinity, sodicity, toxic ions, trace elements (heavy metals and organic micropollutants), residual chlorine, nutrients, anions and cations (Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO^{3-}, C^{l-}, SO_4^{2-}), boron, etc.	Crop growth and quality, Soil properties	FAO and some national guidelines, some water reuse regulations
Mitigation of technical constraints	Chemical, biological and general parameters	Suspended solids, residual chlorine, redox potential, hardness, etc.	Biofilm growth and clogging of distribution and irrigation systems	FAO (1985, 1992), ISO water reuse guidelines (ISO 16075-3)

* SAR – sodium adsorption ratio.

Source: Authors' own elaboration.

As a rule, the environmental and agronomic risks from water reuse for irrigation relate to uncontrolled or high industrial wastewater discharge in municipal sewers (e.g. high concentrations of heavy metals or organic micropollutants). In coastal areas, the primary risk is high salinity and sodicity of wastewater caused by seawater intrusion in municipal sewers (e.g. high rates of infiltration, especially under bad weather and high tide conditions). Experience with biological wastewater treatment (e.g. activated sludge) shows that the large proportion of heavy metals and refractory organic micropollutants are concentrated in sludge. Consequently, the field application of polluted wastewater sludge and the reclamation of industrial wastewater represent a higher risk for agriculture. For this reason, French regulation (Légifrance 2010) on water reuse does not require the monitoring of trace contaminants if municipal sludge quality is in compliance with the regulation on sludge spreading in agricultural areas.

3.2. Definition of the main categories of water reuse for agricultural irrigation

Despite the complexity of existing use categories definitions, a general decision tree can be developed. The first stage is to determine whether a crop is considered edible or not. For edible crops, the next stage is to ascertain whether the crop is eaten cooked or raw. Here, cooking is viewed as an additional treatment (or barrier) favouring public protection. Direct contact between crops and reclaimed water is an additional important factor. It should be recognized, however, that the entire transmission chain should be considered. This includes factors such as the use (or not) of low-quality water to irrigate or wash food crops, the sale of such uncooked crops to markets, restaurants, and so on – all of which might present risks of pathogen transmission arising from crop handling or the contamination of cooking environments.

For those crops that are not edible, it is important to consider whether the area under irrigation is restricted or not. In restricted areas, the likelihood of public exposure is lower than in a non-restricted site. The risk of disease transmission is related to the quality of the reclaimed water and the degree of human contact with that water. Finally, sprinkler irrigation is associated with a higher risk than flood, furrow or drip irrigation, due to the potential for disease transmission from aerosols or windblown spray if a low level of disinfection is provided.

In many countries, crops eaten raw are generally considered to present the greatest potential for disease transmission associated with the use of reclaimed water for irrigation. However, this is not always the case. For example, some regulations recommend more stringent standards for public lawns than for crops eaten raw.

3.3. Key international and national water reuse regulations and guidelines

Water reuse standards or guidelines vary with the type of application, regional context and overall risk perception. In practice, these factors are expressed through different water quality and treatment requirements as well as criteria for operation and reliability. The most stringent guidelines and regulations operate on the basis of the precautionary principle, which demands high water quality and intensive treatment, leading to lower health risks without additional specific measures. However, similar health protection can be achieved by means of additional health protection barriers, as demonstrated by WHO (2006). This approach allows for the use of less expensive treatment and monitoring, which is within the reach of all countries, but struggles with its implementation where risk awareness is low (Drechsel, Qadir & Galibourg, 2022).

The application of additional health protection barriers and codes of good practices (the multi-barrier approach) could form an essential part of a risk mitigation strategy, as underlined by USEPA (2012). These kinds of measures are as important for farmers and operators as quality requirements for water especially where wastewater treatment is not able to achieve the latter.

Regarding microbial parameters and health protection, current agricultural water reuse regulations and guidelines vary significantly in terms of selected key water quality parameters, threshold levels and monitoring requirements. Table 3.2 illustrates the microbial water quality and treatment requirements of the most important cornerstone water reuse guidelines and regulations followed in many countries.

Concerning trace elements, agronomic and physico-chemical parameters and compounds, the FAO guidelines (Ayers & Westcot, 1985; Pescod, 1992) constitute the key document of reference for the water reuse standards, guidelines and regulations of other organizations and countries. These parameters are of critical importance for the implementation of safe agricultural water reuse practices due to their influence on crops quality and yield, as well as soil properties and productivity.

Table 3.2. Comparison of common water quality criteria for agricultural irrigation of selected guidelines and regulations

Class	Parameter	**WHO** (1989)	**WHO** (2006)	**FAO** (1992[a])	**USEPA** (2012)	**California** (2000)	**Australia NRMMC** (2006)	**ISO 16075-1 to 4** (2015, 2016, 2020)	**European Union** (2020)
		Guidelines	*Guidelines*	*Guidelines*	*Guidelines*	*Regulation*	*Guidelines*	*Guidelines*	*Regulations*
Unrestricted irrigation of food crops/consumed raw	**Microbial indicator**	Faecal coliforms	*E. coli*	Faecal coliforms	Faecal coliforms	Total coliforms (TC)	*E. coli*	Thermo-tolerant coliforms	*E. coli*
	Coliforms, number (cfu or MPP) per 100 mL	≤1 000 crops eaten raw ≤200 for public lawns	10 to 10^5 *E.coli* depending on treatment, additional health barriers and type of crops	≤1 000 (more stringent (<200) for public lawns)	Not detected (daily, seven-day median, 14 max)	≤2.2 (daily, seven-day median, 23 max in 30 days, 240 max)	≤1 (weekly)	≤10 (weekly, 100 max, 95 percentile)	≤10 (weekly, 90 percentile)
	Helminths, eggs/L	≤1	≤1	≤1[b]	NS	NS	NS[d]	NS	NS
	BOD_5, mg/L	NS	NS	NS	≤10 (weekly)	NS	NS[e]	≤5 (average, 10 max)	≤ 10 (weekly)
	Total suspended solids TSS, mg/L				NS				
	Turbidity, NTU				≤2 (online, av. 24 h, 5 max) Membranes ≤0.2 any time	≤2 (online, av. 24 h, 5 max) Membranes ≤0.2 (max 0.5)		≤3 (average, 6 max)	≤5
	Chlorine residual				>1 mg/L (on-line)	>1 mg/L		optional (0.2 to 1 mg/L)	NS
	Log removal requirements (pathogens)	NS	6-7 logs in total via various combinations of pathogen barriers, water treatment and natural die-off	NS	NS	5 log of MS2 bacteriophages of disinfection process	6 log viruses 5 log for bacteria and protozoa	NS	>5 log *E. coli* >6 log coliphages[h] >4 log *Clostridium perfringens*[i]
	Minimum treatment requirements	Stabilisation ponds	List of treatment and non-treatment pathogen barriers which can be combined to achieve the health-based risk reduction target	Series of stabilization ponds	Secondary treatment, filtration, disinfection	Tertiary treatment + disinfection; chlorination Ct 450 mg. min/L	Secondary treatment, filtration and disinfection[f]	Secondary treatment, filtration and disinfection[g] multi-barrier approach supported	Secondary treatment, filtration, disinfection , post-treatment barriers
Others	Coliforms / 100 mL	NS	Restricted irrigation: 3-4 log units removal requirement	NS	Processed/non-food crops ≤200 FC (median, 800 max)	NS	Commercial food crops, pastures, fodder ≤100 to ≤1 000 *E. coli*	≤200 *E. coli for* processed food crops, ≤1 000 for non-food crops (+ 1 log max)	
	Legionella		NS	NS	NS		NS	<1 000 cfu/L if risk of aerosolization (twice a month)	
	Helminths, eggs/L	≤ 1	≤ 1	≤ 1[c]				≤ 1 for categories C, D and E	≤ 1 for pastures or fodder[j]

NS: Not specified

a Based on the WHO 1989 guideline.

b *Ascaris* and *Trichuris* species and hookworms, during the irrigation period.

c For pastures, fodder, cereals and orchards.

d For highest exposures, the verification monitoring also includes *Clostridium perfringens*, somatic and F-specific bacteriophages (weekly), as well as adenovirus and *Cryptosporidium* oocysts (monthly).

e The state regulations in Australia require 10 mg/L of BOD_5 and TSS for category A, the highest exposure and highest water quality.

f A number of specific operational parameters are recommended depending on the given treatment process.

g Different treatment processes are specified for each treatment step.

h Total coliphages or alternatively F-specific or somatic coliphages.

i Spore-forming sulfate-reducing bacteria can be used as an alternative.

j The monitoring frequency depends on the initial count of helminth eggs.

Source: Authors' own compilation.

3.3.1. WHO water reuse guidelines

The first set of World Health Organization water reuse guidelines were published in 1973 and included recommended criteria for several uses, including crop irrigation and potable reuse. In 1985, WHO and other international organizations sponsored a meeting of experts to review the use of reclaimed water for agriculture and aquaculture, in particular in arid and developing countries. The experts concluded that the health risks for those applications were minimal and the current guidelines were overly restrictive. Consequently, revised guidelines were developed and published (WHO, 1989). Compared to the original WHO guidelines, the revised version proposed less stringent maximum concentration levels for food crops eaten raw with respect to faecal coliforms, with the recommended threshold limit increasing from 100 FC/100 mL to 1 000 FC/100 mL (Table 3.2). A more stringent standard of 200 FC/100 mL was suggested for the irrigation of public lawns. The technology recommended for water reuse was stabilization ponds or any equivalent treatment processes. Several countries have used the WHO 1989 guidelines as the basis for their agricultural reuse standards. In the absence of recommendations for suspended solids in the WHO guidelines, national standards have typically fixed TSS concentrations at between 10 mg/L and 30 mg/L.

After in-depth reviewing of the epidemiological evidence linking disease transmission to irrigation with reclaimed water led to a third edition of the WHO-FAO-UNEP guidelines for the safe use of wastewater in agriculture (WHO, 2006). This edition benefited from scientific advances in microbiological risk assessment and drew on the Australian Water Reuse Regulations (NRMMC, 2006).

Rather than relying on water quality thresholds, as was the case with the 1973 and 1989 editions, the revised 2006 WHO-FAO-UNEP guidelines adopt a comprehensive risk assessment and risk management framework. This risk assessment framework identifies and distinguishes different vulnerable communities (e.g. agricultural workers, consumers, and members of communities where wastewater-fed agriculture is practised), and considers the trade-offs between potential risks and nutritional benefits in a wider development context. Accordingly, the WHO-FAO-UNEP approach recognizes that conventional wastewater treatment may not always be feasible, particularly in resource-constrained settings, and offers alternative (multi-barrier) measures that can reduce the health risks, in particular for consumers of wastewater irrigated crops.

The performance targets developed by WHO-FAO-UNEP in 2006 for unrestricted and restricted irrigation provide adequate health protection, and attain the health-based target of ≤10^{-6} DALY

Disability adjusted life year) per person per year. This tolerable health risk can be achieved through various options and combinations of treatment, irrigation methods, low- and high-rate growing crops, types of crop, and additional health protection barriers such as natural die-off, product washing, peeling or cooking, and so on. For example, the microbial concentration levels for verification monitoring recommended for unrestricted irrigation of food crops (Table 3.2) vary from 10 *E. coli*/100 mL (treatment only) to 10 000 *E. coli*/100 mL (drip irrigation of high-growing crops).

However, the increased complexity of the 2006 edition, with its emphasis on quantitative microbial risk assessment (QMRA) to determine local health-based targets, has limited its widespread adoption, as it was not the case with the previous 1989 edition (Scott *et al.*, 2010; Drechsel, Qadir & Galibourg, 2022). To provide assistance with implementation, WHO has developed a step-by-step health risk-based Sanitation Safety Planning approach for managing and monitoring sanitation systems (WHO, 2022).

In addition to risks from pathogen contamination, wastewater may contain chemical contaminants from industrial discharge or stormwater runoff. The 2006 WHO-FAO-UNEP guidelines provide maximum tolerable soil concentrations of various toxic chemicals based on human exposure through the food chain. With regard to irrigation water quality, WHO refers to the FAO guidelines, which focus on plant growth requirements and limitations (Ayers & Westcot, 1985; Pescod, 1992) through the food supply chain.

3.3.2. FAO guidelines

The most commonly cited FAO health protection recommendations were developed on the basis of the WHO 1989 guidelines (Pescod, 1992), and took into account the epidemiologic studies. Depending on the risk of contact, three water quality categories were defined: (A) Irrigation of crops likely to be eaten uncooked, sports fields and public parks; (B) Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees; and (C) localized irrigation. Faecal coliforms were used as a microbial indicator only for category A (≤1 000 FC/100 mL, Table 3.2), where helminth eggs were introduced for the irrigation of pastures, fodder, cereals and orchards. These guidelines were indirectly superseded when FAO, as part of UN-Water, adopted the WHO (2006) guidelines as the official position of the United Nations.

General physico-chemical parameters (suspended solids, biological oxygen demand BOD, etc.) were not specified in the FAO guidelines, but agronomic parameters and trace elements that could have adverse impacts on crops and soils were well defined and used as a basic reference worldwide (Ayers & Westcot, 1985; Pescod, 1992).

The parameters of agronomic significance (see Table 3.1) include a number of specific properties of water that are relevant to the yield and quality of crops and the maintenance of soil productivity, as well as protection of the environment and irrigation systems. As emphasized by Pescod (1992), the FAO water quality classifications are only indicative guidelines and their application must be adjusted to local conditions. In fact, the suitability of water for irrigation depends greatly on the climatic conditions, the physical and chemical properties of the soil, the salt tolerance of the crop grown and the management practices. The quality of irrigation water is of particular importance in arid zones where extremes of temperature and low relative humidity result in high rates of evaporation with consequent deposition of salt, which tends to accumulate in the soil profile.

As shown in Table 3.3, the FAO classification for irrigation water includes three groups of potential crop yield problems based on salinity, sodicity, toxicity and miscellaneous hazards: no impact, slight to moderate impact and severe impact (Ayers & Westcot, 1985).

The most important agronomic parameter is the salinity of irrigation water, expressed either as total dissolved solids (TDS, mg/L) or as electrical conductivity (ECw), and measured in dS/m (Table 3.3). In general, TDS over 2 000 mg/L or conductivity higher than 3 dS/m could represent a significant quality problem for irrigation. In fact, dissolved salts increase the osmotic pressure of soil water and, consequently, lead to an increase of the energy which plants must expend to take up water from the soil. As a result, respiration is increased and the growth and yield of most plants decline progressively as osmotic pressure increases.

Compared to 1985 (Ayers & Westcot, 1985), in 1992 FAO slightly increased the maximum threshold limit for salinity from 2.7 dS/cm to 3.0 dS/cm (Pescod, 1992). On the basis of research and practical observations, the classification of saline water has been reconsidered, with the maximum threshold value increasing from >3 mS/cm to >6 mS/cm (Rhoades *et al.*, 1992; Lazarova & Bahri, 2005). FAO has since produced the updated salt tolerance value for major crops in FAO Irrigation and Drainage

Table 3.3. FAO guidelines for parameters with agronomic significance for agricultural irrigation

	Parameter	Pescod, 1992; Ayers & Westcot, 1985		
		No impact	Slight to moderate impact	Severe impact
Impact on crop growth	**Salinity**			
	Electrical conductivity, ECw dS/m	<0.7 (<1.0)	0.7 (1.0) to 3.0 (2.7)	>3.0 (>2.7)
	Total dissolved solids, TDS, mg/L	<450	450 to 2 000	>2 000
	Sodicity – effect of sodium ions expressed by SAR* versus ECw			
Impact on infiltration rate	SAR 0 to 3	ECw >0.7	0.7 to 0.2	<0.2
	SAR 3 to 6	ECw >1.2	1.2 to 0.3	<0.3
	SAR 6 to 12	ECw >1.9	1.9 to 0.5	<0.5
	SAR 12 to 20	ECw >2.9	2.9 to 1.3	<1.3
	SAR 20 to 40	ECw >5.0	5.0 to 1.9	<1.9
	Specific ion toxicity			
Impact on crop growth	Sodium Na+, surface irrigation sprinkler irrigation	SAR <3 <3 meq/L	SAR 3 to 9 >3 meq/L = 69 mg/L	SAR >9
	Chloride Cl^-, surface irrigation sprinkler irrigation	<4 meq/L = 113 mg/L <3 meq/L	4 to 10 meq/L (to 15) >3 meq/L = 85 mg/L	>10 meq/L = 282 mg/L (>15)
	Boron	<0.7 mg/L (<1)	0.7 (<1) to 3.0 mg/L	> 3.0 mg/L
	Trace elements, maximum concentration, mg/L Cd, Mo – 0.01 ; Se – 0.02; Co – 0.05; As, Be, Cr, V – 0.1; Cu, Mn, Ni – 0.2; F – 1.0; Zn – 2.0; Li – 2.5; Al, Fe, Pb – 5.0			
Miscellaneous effects	Nitrogen, mgN/L	<5	5 to 30	>30
	Bicarbonates HCO_3^-, meq/L	<1.5 = 91.5 mg/L	1.5 to 8.5 (7.5)	>8.5 = 519 mg/L (>7.5 = 456 mg/L)
	pH	6.5 to 8.0		
	Parameters related to **clogging potential** in drip irrigation			
Clogging of drippers	Suspended solids, mg/L	<50	50 to 100	>100
	Dissolved solids, mg/L	<500	500 to 2 000	>2 000
	Manganese Mn, mg/L	<0.1	0.1 to 1.5	>1.5
	Iron Fe, mg/L	<0.1	0.1 to 1.5	>1.5
	Hydrogen sulphide H_2S, mg/L	<0.5	0.5 to 2.0	>2.0
	Bacterial count, number/mL	<10 000	10 000 to 50 000	>50 000

*SAR – sodium adsorption ratio, which reflects the amount of sodium relative to calcium and magnesium, expressed in meq/L
Source: Authors' own elaboration.

Paper 61 on agricultural drainage water management in arid and semi-arid areas (FAO, 2002) as well as in the FAO AquaCrop model (2017) that accommodated the yield response of herbaceous crops to water and is particularly well suited to conditions in which water and salinity are limiting factors. It is important to emphasize that FAO and some national water reuse guidelines and regulations provide lists of crops classifications according to their tolerance and sensitivity to salinity. Salt tolerance also depends on the type, method and frequency of irrigation (see Chapter 5).

It is important to emphasize that FAO and some national water reuse guidelines and regulations provide lists of crops classifications according to their tolerance and sensitivity to salinity. Salt tolerance also depends on the type, method and frequency of irrigation (see Chapter 5). Sodium is a unique cation because of its effect on soil properties. When present in the soil in exchangeable form, sodium causes adverse physical-chemical changes, particularly to soil structure, which results in the dispersion of particles and, consequently, in reduced infiltration rates of water and air into the soil. The most reliable index of the sodium hazard of irrigation water is the sodium adsorption ratio (SAR). A threshold value of SAR of less than 3 indicates no restriction on the use of recycled water for irrigation, while severe damage could be observed when the SAR exceeds 9, in particular for surface irrigation. At a given SAR, the infiltration rate decreases when salinity increases. Therefore, SAR and ECw should be used in combination to evaluate the potential adverse impact (see Chapter 5).

Many ions which are harmless or even beneficial at relatively low concentrations may become toxic to plants at high concentrations. This effect may be a consequence of direct interference with the metabolic processes or indirect effects on other nutrients, which might be rendered unavailable. Toxicity normally results in impaired growth, reduced yield, changes in the morphology of the plant and even its death (see Chapter 5). The most common phytotoxic ions that may be present in municipal effluents in concentrations high enough to cause toxicity are boron (B), chloride (Cl) and sodium (Na). Each can cause damage individually or in combination. Boron can become toxic at levels only slightly greater than those required by plants for good growth. Specific lists of crops tolerance and sensitivity to these three toxic ions are provided by FAO (Ayers & Westcot, 1985) and other publications (see Chapter 5).

In addition to sodium, chloride and boron, many trace elements are toxic to plants at low concentrations. Trace elements are not normally included in routine analysis of regular irrigation water, but attention should be paid to them when using treated municipal effluents, particularly if contamination with industrial wastewater discharges is suspected. These include (Table 3) aluminum (Al), beryllium (Be), cobalt (Co), fluoride (F), iron (Fe), lithium (Li), manganese (Mn), molybdenum (Mo), selenium (Se), tin (Sn), titanium (Ti), tungsten (W) and vanadium (V). Heavy metals include also a special group of trace elements that have been shown to create definite health hazards when taken up by plants, as for example arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg) and zinc (Zn). According to the recommendations of the US National Academy of Sciences (Asano *et al.*, 2007), distinction is made between permanent irrigation of all soils with low maximum concentration levels, and up to 20 years irrigation of fine-textured neutral to alkaline soil, where higher concentrations of trace elements can be tolerated.

In addition to adverse effects on crops and soil properties, reclaimed water quality could lead to a number of technical constraints, such for example clogging of localized irrigation, e.g. drippers and sprinkler noses. Table 3 illustrates also the FAO water quality requirements to prevent clogging in localized irrigation systems (Pescod, 1992). High content of suspended solids, iron, manganese and bacterial growth are the most common water quality parameters inducing emitter clogging.

In recent years, FAO started collaborating with the U.S. Food and Drug Administration on the application of Whole-Genome-Sequencing (WGS) to study pathogens and track their path from water to food in order to prevent food contamination at its source. By incorporating water quality into food safety considerations and applying genomic surveillance to this process, WGS is enabling countries to address water and food quality as an integrated issue. The approach allows to improve supply chain controls and to support more efficient and safe food production . It also allows to monitor water quality forearly pathogen detection . The COVID-19 pandemic made the world realize the critical role WGS has in environmental monitoring .

3.3.3. United States Environmental Protection Agency (USEPA) guidelines

The revised 2012 USEPA guidelines follow three earlier editions (1980, 1992, 2004) and were developed in collaboration with the United States Agency for International Development (USAID). They aim to make the water reuse process easier to implement, based on information drawn from databases in different states and global experience. Recent innovations in treatment technologies, best practices and public outreach strategies are presented and illustrated in chapter 9 with a number of case studies from around the world. The 2012 edition maintains the highly stringent requirements for microbial parameters (e.g. no detectable faecal coliforms in 100 mL) and the high level of treatment, which includes secondary treatment, filtration and disinfection for food crops irrigation (see Table 3.2). The USEPA reuse guidelines are intended to be used as Federal recommendations for water reuse criteria, but states have the authority to develop even more stringent criteria (but not lesser than Federal guidelines).

3.3.4. California Water Recycling Criteria

The State of California has been a leader in the development of comprehensive water reuse regulations, with the California Department of Health Services revising its criteria most recently in 2000 (State of California, 2000). California's Water Recycling Criteria, also known as the Title 22 Water Reuse Criteria, provide a very comprehensive set of water quality and other requirements, and have served as the basis for similar criteria in other states and countries. These criteria have been considered as among the most stringent and restrictive of their type, but have also been recommended for their very comprehensive and easy-to-implement approach. Similar to the USEPA guidelines, the state criteria require a high level of disinfection for almost total coliform inactivation (<2.2 TC/100 mL, Table 3.2) for unrestricted food crop irrigation. In this case, total coliforms are used as the principal microbial indicator, and are considered as conservative compared to faecal coliforms and *E. coli*. In addition, a specific treatment process is required for the production of high-quality recycled water that includes – after conventional secondary treatment – at a minimum filtration and disinfection at levels that meet state process requirements.

The California Water Recycling Criteria also include conservative requirements for water quality monitoring, treatment train design and process operation. For example, the turbidity requirements for Title 22 treatment (conventional tertiary treatment with disinfection) state that turbidity should be less than 2 NTU (max 5 NTU), and if membranes are used, the turbidity cannot exceed 0.2 NTU more than 5 percent of the time within a 24-hour period or exceed 0.5 NTU at any time.

In California, specific laws and regulations mandate water reuse under certain conditions (State of California, 1998). For example, Section 13550 of the California Water Code states that the use of potable domestic water for non-potable uses, including, but not limited to, cemeteries, golf courses, highway landscaped areas, and industrial and irrigation uses, is considered a waste or an unreasonable use of the water if reclaimed water is available that meets certain conditions (i.e. adequate quality, reasonable cost, and no adverse effect on public health and environment).

3.3.5. Australian Regulation for Water Recycling

In 2006, the Australian Environment Protection and Heritage Council in conjunction with the Natural Resource Management Ministerial Council issued the "Australian Guidelines for Water Recycling: Managing Health and Environmental Risks" (NRMMC, 2006). Developed on the basis of existing state regulations designed to address water crises and improve the management of health and environmental risks, these guidelines cover a broad range of applications, including agricultural and landscape irrigation, urban uses, managed aquifer discharge, and stormwater harvesting and recycling. They include a comprehensive risk assessment developed for health and environmental risks using DALYs for human risks, as explained previously for the WHO guidelines (2006).
In principle, the guidelines recommend qualitative microbial risk assessment, although for some pathogens or contaminants, it may be possible to carry out a quantitative microbial risk assessment, in order to provide a numerical estimate of risks. This risk assessment approach consists of the following steps: (i) define a tolerable maximum additional burden of disease, (ii) derive tolerable risks of disease and infection, (iii) determine the required pathogen reduction to ensure that the tolerable disease and infection risks are not exceeded, (iv) determine how the required pathogen reductions can be achieved, and (v) put in place a system for verification monitoring. Preventive measures are recommended to lower the identified risks to acceptable levels.

As with the USEPA and California water quality requirements, a very high level of disinfection is required for almost total coliform removal (<1 *E. coli*/100 mL for irrigation of food crops consumed raw; see Table 3.2). The threshold limits for commercial food crops vary from <100 to <1 000 *E. coli*/100 mL depending on the treatment train). In addition, verification monitoring is proposed to demonstrate adequate log removal of not only bacteria, but also viruses and protozoa (defined by means of the microbial health risk assessment). Risk assessment and monitoring requirements are highly restrictive and conservative compared to other regulations. Chemical and agronomic parameters are also included.

3.3.6. ISO Standards on water reuse

In 2015, the first ISO standard on water reuse for irrigation was issued in three parts covering the main steps of project development (ISO 16075-1 to 3, 2015). Part 1 contains guidelines for the development and the execution of projects intending to use treated wastewater for irrigation taking into consideration the parameters of climate and soil. Part 2 is focused mostly on wastewater treatment and water quality, while Part 3 is providing comprehensive recommendations for the management of distribution system and irrigation material. Part 4 was published a year later and is covering water quality and soil and aquifer monitoring to mitigate health and environmental risks (ISO 16075-4). WHO (2006) and the State of California Water Recycling Regulations (2000) were used as the basic reference points for the development of this standard.

ISO defined five categories of water quality for irrigation of which category A requires almost total disinfection (≤10 *E. coli*/100 mL, Table 2) for irrigation of crops consumed raw. The recommended treatment to achieve this quality is the conventional combination of secondary treatment, filtration and disinfection. In 2020, the second edition of ISO 16075-2 broadened the options available for risk reduction to include different barriers from farm to fork based on WHO (2006) and USEPA (2012).

In 2018, ISO issued a comprehensive guideline on health risk assessment for non-potable reuse, including agricultural irrigation, based on qualitative health risk assessment (ISO 20426).

3.3.7. European Commission Water Reuse Regulation

The Water Reuse Regulations of the European Commission were published in 2020 to harmonize minimum water quality and monitoring requirements for the safe reuse of treated urban wastewaters in agricultural irrigation (EU regulation 2020/741). Risk management provisions are included to assess and address potential health and environmental risks, as well as permit requirements. The regulation defined four categories of water quality on the basis of existing guidelines and regulations of member states and leading international standards (Australia, ISO, WHO). For the highest reclaimed water quality, cat. A, which is used for the irrigation of all food crops consumed raw and all irrigation methods, a restrictive threshold is required of ≤10 *E. coli*/100 mL or under the detection limit (see Table 3.2). A relatively conservative threshold is also required for cat. B of ≤100 *E. coli*/100 mL for the irrigation of 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 those used to feed milk- or meat-producing animals. Cat. C is used for the same applications, but in the case of drip irrigation higher concentration is authorized of ≤1 000 *E. coli*/100 mL. In addition, verification of the log removal of bacteria, viruses and protozoa is required for cat. A, the most stringent category. While the guideline is referencing the multi-barrier approach supported by WHO (2006) and ISO 16075-2 (2020), its recommendation focus is on barriers to achieve the EU water quality threshold, not like WHO (2006) on health-based targets.

3.4. Conclusion

The development and enforcement of water reuse standards is an essential step in the social acceptance of water recycling. However, in some cases, regulations could represent a challenge and a burden for water reuse, as for example in the case of very restrictive requirements based on the precautionary principle. For example, health risk-based regulations for irrigation, such as those developed in Australia and used as the basis for the new European regulations, require an additional health risk assessment (qualitative or Quantitative Microbial Risk Assessment, QMRA) and validation of log removal of treatment technologies, in addition to water quality monitoring. These new requirements lead to significantly higher permit and operation costs, without any guarantee of lower health risks or better process reliability. A recent review performed by leading experts (Olivieri *et al.*, 2014) demonstrated that agricultural water reuse following the treatment-based approach used for years in the United States, in particular in California, do not increase public health risks and that modifying the standards to make them more restrictive will not improve public health.

Water reuse standards must be adapted to the country’s specific conditions (administrative infrastructure, economy, climate, etc.), and should be economically viable and coordinated with the country’s water conservation strategy. Regulated and well-managed irrigation under WHO guidelines (or similar standards) can protect public health and the health of farm workers at affordable cost. While the WHO (2006) supported multi-barrier approach is increasingly accepted, like in the 2020 versions of the ISO and EU guidelines, water quality targets continue to have priority where they can be achieved, compared to the broader concept of the WHO (2006) supported health-based targets.

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Chapter 4

Risk analysis and risk mitigation approaches: Waterborne pathogens that become foodborne pathogens through irrigation

Ana Allende and Pay Drechsel

Agricultural water is used extensively during produce-growing activities (e.g. irrigation, fertilization, frost protection, pesticides application), harvesting, marketing (e.g. rinsing) and cooling (e.g. hydrocooling). Scientific evidence points to agricultural water as a major risk factor in the contamination of fresh produce (European Commission, 2017). FAO (1995) and WHO (2006) have provided evidence that pathogenic microorganisms represent the single-most important health risk for food safety where any form of water contaminated by domestic wastewater is used for irrigation or in post-harvest food handling. This water can be contaminated through a variety of pathways and can potentially spread bacteria, viruses (see Box 4.1) and parasites to crops, humans and animals.

Box 4.1. COVID-19
Many research groups have successfully detected macromolecules (ribonucleic acid or the RNA) of the SARS-CoV-2 virus in wastewater, which can then be used to monitor COVID-19 in a community (Kitajima *et al.*, 2020). However, the COVID-19 virus is an enveloped virus, which is less stable in the environment and more susceptible to oxidants, such as chlorine, than other types of viruses such as enteroviruses (La Rosa *et al.*, 2020). As a result, the presence of infectious SARS-CoV-2 viruses in treated or untreated wastewater has not been demonstrated, making the risk of a faecal-oral transmission of SARS-CoV-2 via contaminated drinking water or irrigated food low. It has also been suggested that conventional wastewater treatment is adequate to control the transmission of COVID-19, as RNA fragments of SARS-CoV-2 have not been detected in fully treated sewage (WHO & UNICEF 2020).

Practical observations indicate that farmers use the water they have available. However, water availability and quality differ from one context to another, and may be fit to use only for certain purposes. Establishing fit-for-purpose water use requires assessment of the water source, analysis of the treatment options to ensure appropriate quality for end use and evaluation of multiple barrier processes (Neale *et al.*, 2020). The end use of the food product (e.g. if eaten raw) must be also considered (FAO & WHO, 2019).

To guarantee not only the suitability of the water, but also the sustainability of the system, it is important to establish the minimum requirements according to the "fit-for-purpose" approach, which necessitates setting water-quality goals in relation to end user needs (Helmecke, Fries & Schulte, 2020).

Current good agricultural practices (GAP) should include practical knowledge adequate to enable growers to predict potential contamination outcomes, identify suitable preventive measures and prioritize risk management efforts. These activities should be integrated into risk analysis and risk mitigation approaches, as already reflected in several guidelines for water reuse, such as the World Health Organization (WHO) Health Guidelines for the Use of Wastewater in Aquaculture and Agriculture and the ISO Guidelines (16075) for Treated Wastewater Use for Irrigation (Helmecke, Fries & Schulte, 2020).

4.1. Potential microbiological risks and corrective actions

While a variety of water sources are available for field operations and irrigation, extensive knowledge is needed to relate risk factors associated with the transfer coefficients for pathogens by source, concentration and use (CPS, 2014). Of utmost importance is the selection of the water source as well as the intended use of the water to ensure that irrigation water does not represent a potential source of contamination. When irrigation water is contaminated, the main route of exposure to microbial hazards is ingestion, including the consumption of irrigated crops and the ingestion of droplets produced by sprays (EPHC, NRMMC & AHMC, 2006).

Table 4.1 summarizes the main occupational and consumption-based human health risks from irrigating vegetables with polluted water. Although some respiratory and skin illness can be also attributed to pathogenic microorganisms present in contaminated water, there is a lack of information about their significance, compared with consumption-related risks, which can reach a much larger community if the vegetables are intended for sale.

Table 4.1. Main human health risks from irrigating vegetables with polluted water

Type of risk	Health risk	Group at risk	Exposure pathway
Occupational risks (contact)	• Parasitic worm (helminth) infections with for example roundworms (e.g. Ascaris) via ingestion of worm eggs or though larvae penetrating the skin (e.g. hookworms) • Diarrhoeal diseases, especially in children, linked to enteric viruses • Skin infections causing itching and blisters on hands and feet, but also dermatitis (eczema).	• Farmers/field workers • Children playing on the farm	• Hand or fingers (in contact with contaminated water and soil) put in the mouth • Larvae enter the skin of individuals working barefoot
		• Traders and market vendors • Kitchen staff or household members engaged in food preparation	• Hand or fingers in contact with contaminated crops put in the mouth, incl. vegetables washed on-farm or in markets with unsafe water
Consumption-related risks (food chain)	• Bacterial and viral infections such as typhoid, hepatitis A, viral enteritis which mainly cause diarrhoea, but also e.g., cholera. • Parasitic worms such as *Ascaris*	• Consumers at home or of street food • Farmers or children eating on the farm	• Consumption of contaminated vegetables or fruits that have not been carefully peeled, washed, sanitized or cooked

Source: Modified from FAO. 2019. On-farm practices for the safe use of wastewater in urban and peri-urban horticulture: A training handbook for Farmer Field Schools. Second edition. Rome.

One of the main challenges facing growers is determining whether the quality of the available water source is suitable for the intended use. This requires understanding the potential microbiological risks linked to the agricultural water. Ascertaining whether the microbial quality of water is acceptable for different agricultural uses and how the agricultural practices, crop type and climatic conditions affect microbial quality is not an easy task (CPS, 2014). Many international guidelines and regulations require growers to take adequate measures, as appropriate, and to use potable or clean water, whenever necessary, to reduce the risk of microbial contamination of produce via water. However, instead of focusing on where potable water or other water quality types can be used, it is more productive to articulate an assessment of the water's fitness for the intended purpose (FAO & WHO, 2019). In fact, an increasing number of competent authorities support the establishment of risk management approaches based on risk and scientific evidence.

Once the potential risks have been identified and, where possible, the minimum microbial requirements established, it is important to understand which corrective actions need to be in place to ensure that potential microbial contaminants, if present in the water source, are eliminated. Suitable intervention strategies should be implemented by growers to reduce food safety risks in fresh produce. Table 4.2 summarizes the occupational risks and reduction measures and relevant considerations for end users.

Table 4.2. Occupational risk reduction

<table>
<tr><th>Kind of occupational risk</th><th>Risk reduction measures</th><th>Considerations</th></tr>
<tr><td>Hand contact with water or irrigated crops and soils, and possibility of hand-mouth contact (farmers, traders)</td><td>• Targeted risk reduction (hygiene promotion) programmes
• Use of gloves for crop handlers
• Availability of clean water for drinking and handwashing
• Frequent handwashing with soap, especially before eating in the field
• Chemotherapeutic control (de-worming medicine) especially for children playing on farm up to three times a year in endemic areas</td><td rowspan="2">Awareness raising about risks and good hygiene is important as

a) not all farmers or traders are aware that the used irrigation water is unsafe from a pathogenic perspective

b) protective clothing has a cost factor and can limit mobility and comfort in (hot) tropical climates, and its adoption requires support. Monitoring of farmer compliance with health directives might work in some regions, while in others incentive systems (e.g. "best urban farmer or farming community") could encourage compliance.</td></tr>
<tr><td>Contact with water and soils via feet and legs</td><td>• Targeted risk reduction (hygiene promotion) programmes
• Avoiding walking into streams or ponds to fetch water
• Use of irrigation systems which minimize water-body contact
• Use of sandals, shoes or ideally boots by field workers
• Frequent body (leg and feet, hand) washing with soap
• Chemotherapeutic control (de-worming medicine) for farm workers if feasible</td></tr>
</table>

Source: Authors' own elaboration.

4.2. Overview of risk analysis frameworks

Current approaches require growers to develop and implement safety management systems and to perform risk assessments on irrigation water sources throughout the crop production cycle (i.e. field history, water sources, animal manures and worker hygiene to reduce microbial risks) (Allende & Monaghan, 2015). The WHO Health Guidelines for the Use of Wastewater in Aquaculture and Agriculture replace the standard approach used for water quality testing for faecal coliforms with a risk assessment/risk management-based approach that involves more flexible guidelines based on attributable risks and disability adjusted life years (De Keuckelaere *et al.*, 2015; WHO, 2006). However, the term "risk assessment" when used by growers usually refers to a general and qualitative approach based more on expert opinion and experience, as required by Good Agricultural Practices (GAP), than full implementation of a risk analysis (Monaghan *et al.*, 2017).

The Codex Alimentarius, also known as the "Food Code", is a collection of standards, guidelines and codes of practice adopted by the Codex Alimentarius Commission (CAC), which forms the central part of the Joint FAO/WHO Food Standards Programme. The CAC recognize that water can be an important source of contamination of food, and have recently issued a call through the Codex Committee on Food Hygiene (CCFH) for the safe use of water in food production, with a particular focus on primary production of fresh produce. The report of a joint FAO/WHO expert meeting, entitled "Safety and Quality of Water Used in Food Production and Processing" (otherwise known as the JEMRA report) (FAO & WHO, 2019) represents a first attempt to implement such a broad approach. In recent years, most Codex documents as well as legislative proposals have highlighted the need to implement a risk-based approach for safe water reuse, and indicated the need to perform assessments to determine fitness for specific water uses. An increasing number of recent research studies have also focused on evaluating the microbial quality of irrigation water used for the production of fresh produce and its significance as a source of contamination.

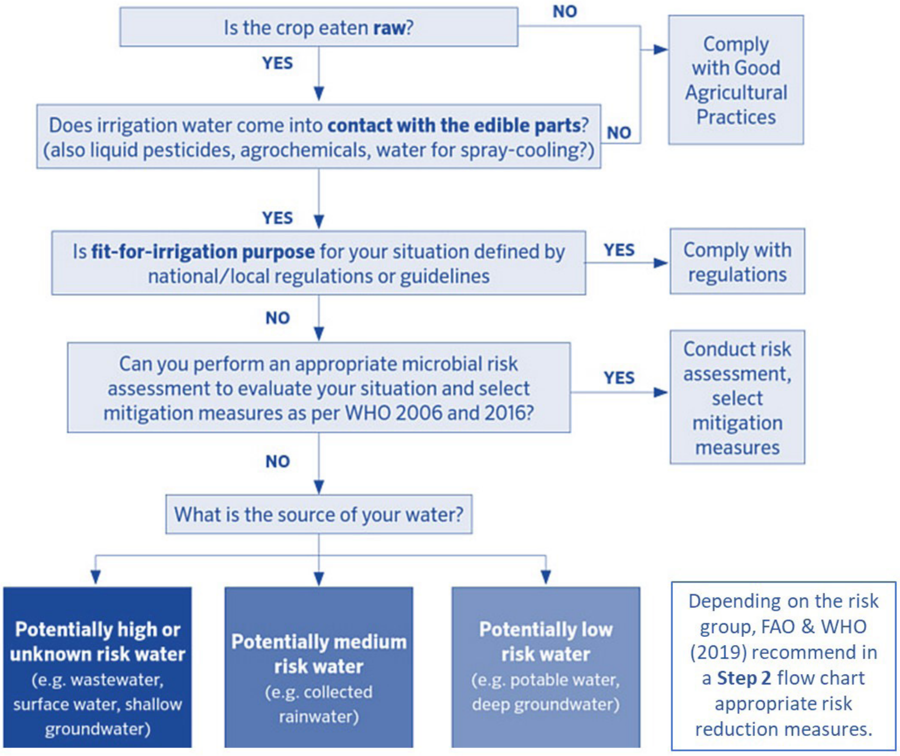
Agricultural water risk assessments rely on data from microbiological analysis, epidemiological studies and/or quantitative microbial risk assessment (QMRA) (Bos, Carr & Keraita, 2010). In most cases, QMRA is applied to establish links between concentrations of pathogenic microorganisms in agricultural water and the probability of illness. However, it should be noted that farmers in most countries where water quality guidelines are of relevance do not have access to QMRA data. For this reason, many guidelines and quality standards provide growers with directions on the minimum factors to be considered when assessing the risk of their pre-harvest agricultural water systems. Four principal steps should be included in the risk assessment: 1) identification of potential hazards that may be present in the agricultural water source; 2) the water delivery system; 3) the application method, and 4) the intended use of the crop.

Risk analysis is usually performed using Decision Support Systems (DSS). Such systems help farmers – and everyone else who makes decisions - to select the best solution during the decision-making process. In this respect, several approaches have been applied to ensure water is of appropriate quality for its intended use. In primary agricultural production, DSS provides growers with a tool to perform risk assessments of water used based on a combination of information related to the water source, the irrigation method, the type of crop and consequently potential contact with the edible portion of the crop (European Commission, 2017).

On-farm, qualitative, risk-based approaches based on DSS usually rely on the development of decision trees (DTs). These useful tools help growers make decisions on the risk level and choice of water source with the aim of avoiding the introduction of hazards that compromise food safety. Many GAP guidelines already include DTs to help growers characterize the water source, identify potential risks, establish the intended use and identify suitable microbial metrics to be applied to irrigation water (FAO & WHO, 2019). Most of the proposed DTs include actions that can be taken on the farm to reduce risks of contamination from agricultural water used during production. For example, the European Commission (2017) guidance document on addressing microbiological risks in fresh fruit and vegetables through good hygiene includes a matrix to support risk assessment of agricultural water based on the combination of water source, irrigation method and potential contact with the crop and commodity type.

The ISO 16075 contains guidelines for the development and execution of projects intending to use treated wastewater (TWW) for irrigation, and considers the parameters of climate and soil. This guidelines classify the TWW based on different quality levels, which are characterized by levels of specific contaminants and further correlated to the various potential uses (ISO 16075-2) (ISO, 2020). Figure 4.1 shows an example of a decision tree that could be used to identify main risk groups linked to the potential contamination of irrigation water as well as critical questions to be asked to enter the second step of the decision tree.

Figure 4.1. Step 1 (Context analysis) of a decision tree for microbiological risk assessments.



Source: Adapted from FAO & WHO. 2019. Safety and quality of water used in food production and processing – Meeting report. Microbiological Risk Assessment Series No. 33. Rome

Similar examples of decision trees have been developed by many international organizations. For instance, the European Commission (2017) guidance document contains similar questions and includes a limited number of sampling recommendations. For a comparison of the strengths and limitations of tools for the assessment of faecal pathways and related risks in the larger urban environement, see Mills *et al.* (2018).

4.3. Available risk mitigation measures

In primary production, the quality of water sources can vary widely both over the short term and the long term, as in the case of surface water (e.g. river, canals). This variation reduces the usability of water monitoring as a risk management tool and triggers the need for fit-for-purpose risk mitigation measures that are commensurate with the variations observed.

QMRA can be used as a tool to assess the impact of different risk mitigation strategies (De Keuckelaere *et al.*, 2015). During studies, it enables the evaluation of scenarios that correspond to the implementation of different intervention strategies. The results provide information on the relative impact of the selected strategies on the contamination of the product. However, as noted earlier, farmers in most countries where water quality guidelines are relevant, lack access to QMRA data. In such cases, the DT approach for the selection of risk mitigation measures is one of the best options.

In the JEMRA report (FAO & WHO, 2019), a DT with a binary (Yes/No) structure is developed to aid in the selection of risk reduction measures for produce. The DT applies a multiple-barrier approach to identify all points where pathogen loads could be increased through the use of poor quality water, as well as to identify intervention strategies that could reduce the contamination of fresh produce. The DT then recommends different preventive measures based on the classification of risk for the water source use by the grower. The preventive measures suggested by FAO & WHO (2019) include the selection of different irrigation systems of lower risk as well as the search for alternative water sources.

The identification and implementation of preventive measures should be based on the multiple barrier principle. According to this principle, multiple preventive measures or barriers are used to control the risks posed by different hazards, thus making the process more reliable. The strength of this principle is that a failure of one barrier may be compensated by the remaining barriers, thus minimizing the likelihood of contaminants passing through the entire system and being present in sufficient amount to cause harm to human health or environmental matrices (Alcalde-Sanz and Gawlik, 2017).

As previously stated by WHO (2011), many control measures may contribute to controlling more than a single hazard, whereas some hazards may require more than a single control measure. This approach has been covered in previous reports and books such as the 2019 meeting report published by FAO and WHO (2019) on the safety and quality of water used in food production and processing, and a publication by Drechsel *et al.* (2010) entitled Wastewater Irrigation and Health. Based on these directives, it is clear that the critical control point concept is similar to the multiple-barrier approach. They conclude that while each individual barrier may not be able to completely remove or prevent contamination, and therefore protect public health, implemented together, the barriers work to provide greater assurance that the water or food will be safe at the point of consumption (Amoah *et al.*, 2011). Case study 1 in the annex describes the research carried out in Ghana where different barriers were tested.

WHO (2016) summarized exposure reductions provided by on-site preventive measures for water safety management and included most of the control measures previously suggested by NRMMC (2006) and WHO (2006). FAO & WHO (2019) addressed qualitative effectiveness of selected control measures for produce, with a focus on small-scale production contexts. The options for risk reduction measurements offer a good overview of the alternatives that could be selected by the grower and the possible effectiveness ratings of water application and treatments (reduction of microorganism levels). In the discussion paper "Options for Updating the 2006 WHO Guidelines", Mara *et al.* (2010) reviewed all the available control measures in the pre-harvest (on-farm) and postharvest contexts. Tables 4.3 and 4.4. summarize the majority of reduction measurements proposed by previous guidelines and reports.

Table 4.3. Risk reduction measures for irrigated food crops

Control measure	Effectiveness (reduction in logs)	Considerations
Use of alternative low-risk water source (e.g., deep well)	5	Depends on groundwater availability, quality, and land tenure secirity to invest e.g. in well drilling
Water treatment options: - Conventional wastewater treatment - Three-tank system on farm - Simple sedimentation pond on farm - Simple water filtration on farm	 1-7 1-2 0.5-1 1-3	 Inactivation of pathogen will depend on type and sophistication of the treatment selected. For conventional treatment systems, see Table 5.2 in WHO (2006)
Crop restrictions (no crops allowed with edible parts eaten raw)	6-7	Inactivation of pathogens will depend on the effectiveness of local enforcement of crop restriction, especially where farmers will face lower income by using alternative crops
Irrigation related options: - Furrow irrigation system - Surface drip irrigation system - Sub-surface drip system - Reduction of soil splashing on leaves	 1-2 2-4 6 1-2	 Pathogen reduction will increase from low- to high-growing crops Use of a rose for watering cans in overhead irrigation
Natural pathogen die-off under dry and ideally hot conditions (assuming no recontamination during handling)	0.5-2 per day	Rate depends on the weather and time interval between the last irrigation event and harvest up to consumption
Postharvest measures (e.g. in markets): - Overnight storage in baskets - Crop preparation (removal of outer, external leaves) - Washing in a bowl - Washing under running tap water	 0.5-1 1-3 1-2 2-3	 Well aerated Cabbage, lettuce Depends on washing duration (min. 1-2 min) and frequency of water change Depends on washing duration (min. 1-2 min)
Kitchen-based processes: - Peeling - Disinfection (5 min) and rinsing with water - Washing 2 min in salt solution - Washing 5 min in a vinegar solution - Cooking	 2 2-3 1-2 2-4 5-7	 Fruits, root crops For example, with permitted chlorine tablets or solutions Effectiveness increases with salt concentration Effectiveness increases with vinegar concentration Option depends on local diets/preferences

Sources: Mara, D., Hamilton, A., Sleigh, A. & Karavarsamis, N. 2010. Discussion paper: Options for updating the 2006 WHO guidelines. WHO, FAO, IDRC, IWMI; Amoah, P., Keraita, B., Akple, M., Drechsel, P., Abaidoo, R.C. & Konradsen, F. 2011. Low-cost options for reducing consumer health risks from farm to fork where crops are irrigated with polluted water in West Africa. IWMI Research Report Series 141, Colombo; FAO & WHO. 2019. Safety and quality of water used in food production and processing – meeting report. Microbiological Risk Assessment Series No. 33. Rome; ISO. 2020. Guidelines for treated wastewater use for irrigation projects. ISO 16075-2. Geneva, International Organization for Standardization. NRMMC. 2006. Australian guidelines for water recycling: Managing health and environmental risks (phase 1). Canberra

Log reductions of pathogens are well defined for most control measures, including water treatment. However, research studies focused on primary production have generated new scientific evidence that enables better understanding of the impact of different preventive measures. For example, a published paper by Belias *et al.* (2020) suggests that the use of a single die-off rate (0.5 log/day) for estimating time-to-harvest intervals across different weather conditions, produce types and bacteria should be reviewed. The study concludes that the rate of die-off appears to be impacted by produce variety, bacteria and weather. As such, the proposed use of the die-off principle (0.5 log/day) as an intervention for contaminated water should be revised to take these factors into account. The reduction attributable to risk mitigation strategies also needs to be updated. However, there is lack of scientific evidence on the performance efficacy of most preventive measurements, including potential synergies. There are many, "average" efficiencies relating to different processes for the removal or inactivation of microorganisms with wide ranges of effectiveness (FAO & WHO, 2019). More research is therefore needed to understand pathogen reduction efficiencies and the performance variation of treatments. Another, and likely much larger challenge relates to the adoption of the recommended risk reduction practices where risk awareness is low and incentives are needed to support behaviour change (Drechsel, Qadir & Galibourg, 2022).

Table 4.4. Comparison of the qualitative effectiveness of selected control measures for produce in the postharvest context

Control measure	WHO (2006)	Mara *et al.* (2010)	WHO (2016)	FAO & WHO (2019)	ISO (2020)
Washing in water	1-2			*	1
Washing in disinfectant	1-2	2-3		**	2
Peeling	2	2	2	**	2
Cooking	5-6	5-6	5-6	*****	6-7

Source: Authors' own elaboration

One of the most plausible solutions for growers faced with the uncertainty of agricultural water quality, like the repeated failure of the only available water source to meet the metrics for indicator bacteria, is the use of water treatments at their end through chlorine injections (Suslow, 2010). In 2015, Allende and Monaghan summarized the most commonly applied water treatments for agricultural water. They reviewed physical and chemical disinfection systems as methods to remove human pathogens from agricultural water sources, although disinfection treatment of irrigation water remains a very limited practice. Nowadays, chemical sanitizers are the most commonly used water treatments, although environmentally friendly alternatives are being demanded, particularly for organic production. In fact, concerns have risen recently regarding both the absence of water treatment and the excessive use of potentially toxic disinfection by-products that accumulate in irrigation water.

Based on Tables 4.3. and 4.4, the most effective single risk barriers where irrigation water is likely polluted remain crop restrictions, drip irrigation, and produce cooking. In the common situation that (i) farmers might not agree with crop restrictions, (ii) drip kits are costly and require more land use security than many informal urban farmers have, and last but not least (iii) post-harvest produce (re)contamination is possible, food safety can eventually only be assured through measures close to consumption, like produce disinfection and washing, or cooking. The high risk of produce contamination along the marketing chain low-income countries is a strong argument for WHO's (2006) shift to health-based targets instead of relying on irrigation water standards.

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Chapter 5

Chemical risks and risk management measures of relevance to crop production with special consideration of salinity

Manzoor Qadir, Pay Drechsel, Francisco Pedrero Salcedo, Laura Ponce Robles, Alon Ben-Gal and Stephen R. Grattan

At least 17 chemical elements are recognized as essential nutrients for plants. Depending on the amount of nutrients that each plant needs, these elements can be categorized as macro- or micro-nutrients. Three of the most structurally important elements are carbon (C), oxygen (O) and hydrogen (H), which are provided by water and carbon dioxide. The remaining soil-derived macro-nutrients include: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulfur (S) and magnesium (Mg). Important micronutrients (or trace elements) include: iron (Fe), boron (B), manganese (Mn), zinc (Zn), copper (Cu), chloride (Cl), molybdenum (Mo) and nickel (Ni).

The challenges for plant nutrition and growth usually derive from an excessively high or low supply of specific nutrients or elements. Moreover, nutrients must be available not only in sufficient amounts but also in appropriate (soluble) form and ratios. The most common disorders are:

- Poor soil fertility resulting in crop nutrient deficiencies, which can be addressed, for example, though application of organic or chemical fertilizers; and
- Excess of salts, micro- or macro-nutrients, or potentially harmful chemicals through irrigation with contaminated water.

This chapter focuses on the second challenge: the risks related to poor irrigation water quality. Where irrigation water of low or marginal quality is used, the different chemical risks that need to be addressed can overlap, but may be categorized as follows:

- Salinity and sodicity and their effects on soils and crops (section 5.1 and sub-sections 5.1.1 and 5.1.2);
- Specific ionic effects and nutrient imbalances caused by salinity, wastewater irrigation and over-fertilization (5.1.3);
- Risks related to heavy metals (5.2);
- Risks from organic contaminants of emerging concern (CEC) such as disinfection by-products, endocrine disruptors, persistent organic pollutants (POPs), pesticides, and pharmaceuticals and personal care products (PPCP) (5.3).

The chapter ends with an extensive review of risk mitigation options for the different identified hazards (Section 5.4), applicable with site-specific adjustments to low- and middle-income countries.

5.1. Salinity and sodicity

All soils contain salts, but salinity becomes an agronomic problem affecting plant growth when certain salts concentrate in the crop's rooting zone. Aside from natural salinity of the soil and its geological parent material, a common source of salts in irrigated soils is the irrigation water itself. Salts in irrigation water stem from dissolution or weathering of rocks and soil. The salts are carried with the water and end up in systems where it is used (Ayers & Westcot, 1985). In the case of water used for irrigation, the crop extracts nearly pure water leaving most of the applied salts in the soil. Salts continue to build up in the root zone unless excess water (rain or irrigation) leaches them below the root zone. The suitability of water for irrigation is determined not only by the total amount of salts present but also by the types of salts, the salt tolerance of the crop and irrigation practices. Various soil and cropping problems develop as the total salt content in soils increases, and special management practices are required to maintain acceptable crop yields. Water quality or suitability for use is assessed based on the potential severity of problems that can be expected to develop over long-term use.

Although salt management techniques such as leaching have been recognized as essential for over a century (Hilgard, 1893), and seem straightforward, the long-term sustainability of irrigated lands remains a challenge as irrigation itself impacts other land and water resources in ways that can lower farm productivity over time, particularly in arid and semi-arid areas where most irrigation takes place (Oster *et al.*, 2012). Irrigation in these areas can also degrade the quality of water in downstream reaches, as dissolved salts enter irrigation return flows to the disadvantage of downstream farmers and communities (Wichelns & Qadir, 2015), an outcome which calls for basin-wide salinity management (see Chapters 8 and 9).

This chapter addresses (i) salinity-related water quality parameters in irrigated agriculture; (ii) sources of salts in irrigation water and their potential impacts on water quality, soil characteristics, crop growth, yield and quality; and (iii) pertinent response options based on management strategies.

5.1.1 Salinity and related impacts on soils and crops

Salinity in irrigation water is commonly represented by its electrical conductivity (EC), usually measured with an electrical conductivity meter. The EC is expressed in terms of deciSiemens per metre (dS/m), or as millimhos per centimetre (mmho/cm), both units being numerically equal. EC readings also allow to estimate the amount of total dissolved solids[1] (TDS) as shown in Equation 1a and 1b (Table 5.1).

$$\text{TDS (mg/L)} \approx \text{EC (dS/m)} \times 640 \qquad [1a]$$
(EC from 0.1 to 5 dS/m)

$$\text{TDS (mg/L)} \approx \text{EC (dS/m)} \times 800 \qquad [1b]$$
(EC > 5 dS/m)

The ratio of TDS to EC of various salt solutions ranges from 550 to 700 ppm per dS/m, depending on the compositions of the solutes in the water. For soil extracts in the EC range from 3 to 30 dS/m, the US Salinity Laboratory (1954) also used the following empirical relationship (Equation 2) between EC and the total soluble salts (TSS) concentration (mmol_c/L)[2].

TSS and TDS measure the amount of particles (solids) floating in water, like organic matter, silt, clay, or salts. They can be divided into those particles that are large enough to be held back by a filter which are called total suspended solids (TSS), while the particles that pass through the filter are called total dissolved solids (TDS). TSS values are often related to the turbidity (cloudiness) of water, while TDS include dissolved minerals and salts in the water and are closely related to conductivity or salinity.

[1] The majority of these solids are salts.
[2] 10 mmol_c/L = 1 cmol/L Instead of mol_c we also see mol^+ or mol (eq)/L.

$$TSS\ (mmol_c/L) \approx EC\ (dS/m) \times 10 \qquad [2]$$

The following Equation 3 supersedes in accuracy Equation 2 for most purposes and expresses TSS and EC in terms of $mmol_c/L$ and dS/m, respectively (Marion & Babcock, 1976).

$$\log TSS = 0.99 + 1.055 \ \log EC \qquad [3]$$

Table 5.1. Categories of water resources based on ambient levels of soluble salts

Water category	EC (dS/m)	Salt concentration (TDS, mg/L)	Typical water source
Non-saline	< 0.7	< 450	Drinking and irrigation water
Slightly saline	0.7–2.0	450–1500	Irrigation water; treated wastewater
Moderately saline	2–10	1500–6500	Primary drainage water and groundwater
Highly saline	10–25	6 500–16 000	Secondary drainage water and groundwater
Very highly saline	25-50	16 000–35 000	Very saline groundwater; seawater[1]
Brine	> 50	> 35 000 (or 3.5%)	Hypersaline seawater

[1] Salt concentrations of very highly saline groundwater usually fall within the lower end of this salt concentration range, while salts in seawater are close to the upper end of the salt concentration range.

Sources: Ayers, R.S. & Westcot, D.W. 1985. Water quality for agriculture. FAO Irrigation and Drainage Paper 29, Rev. 1. Rome: FAO; Estefan, G., Sommer, R. & Ryan, J. 2013. Methods of soil, plant, and water analysis: A manual for the West Asia and North Africa region: Third Edition, Beirut: ICARDA

The relative salt tolerance of most agricultural crops is sufficiently well known to elaborate general salt tolerance guidelines. The following general conclusions can be drawn from the crop salt tolerance data (Ayers & Westcot, 1985):

- Full yield potential is typically achievable for nearly all crops when using water with a salinity content below 0.7 dS/m.
- When using irrigation water of slight to moderate salinity (i.e. 0.7-2.0 dS/m), full yield potential is still possible for most crops not sensitive to salinity, but care must be taken to achieve the required leaching fraction to maintain soil salinity within the salt tolerance limit of the crops. Treated sewage effluent commonly falls within this group.
- For higher salinity water (>2.0 dS/m), increasing leaching to satisfy a leaching requirement greater than 0.25 to 0.30 is typically not practicable because of the excessive amount of water required. In such cases, consideration must be given to replacing salt-sensitive crops with more tolerant crops that require less leaching to maintain salts in the root zone within the crop tolerance limits.

The adverse effects of excess salts in the soil solution on crop growth stems from both osmotic and specific ion mechanisms (Läuchli & Epstein, 1990). Salts reduce the osmotic potential of the soil water solution making the water less available for plants. Some crops cope better in this situation than others. If soil solution salinity surpasses crop specific thresholds, the crop yield will be reduced. Crops such as cotton, barley and sugar beet have high salinity thresholds while others such as bean, onion and strawberry have low thresholds. Salinity often affects crops without visible changes to the soil cover; however in severely affected soils, salt crystals are often found on their surface (Figure 5.1).

Figure 5.1. Salt on the soil surface

Source: www.fao.org/3/x8234e/x8234e08.htm#bm08.1.5.

Maas & Hoffman (1977) proposed a piece-wise linear[3] response equation to describe salt tolerance in crops. Two parameters obtained from this equation are: (i) the threshold soil salinity (the maximum allowable soil salinity for a crop without yield reduction), and (ii) the slope (the percentage yield decrease per unit increase in salinity beyond the threshold salinity level). The data serve only as a guideline to the relative capacities of the crops to withstand salinity as considerable variation exists among crops in terms of their ability to tolerate saline environments. The threshold salinity levels and the slope values obtained from the Maas-Hoffman equation can be used to calculate relative yield (Yr) for any given soil salinity exceeding the threshold level by using Equation 4.

$$Yr = 100 - b\,(ECe - ECt) \qquad [4]$$

Where ECt refers to the threshold saturated paste extract salinity level expressed in dS/m above which yields decline, b is the slope expressed in % per dS/m, and ECe is the average electrical conductivity of the saturated soil paste extract[4] of the root zone expressed in dS/m (for ECt and b values see Grieve, Grattan & Maas, 2012). Based on these values, the yield potential of crops can be estimated at specified salinity levels. The capacity of crops to withstand salinity is described in relative terms such as achieving the relative yield potential (Table 5.2). Further datasets on salt tolerance of additional plants and crops are available elsewhere (Grieve *et al.*, 2012; FAO & AWC, 2023, Box 5.1).

Box 5.1. FAO guidelines on brackish water use

The Guidelines on Brackish Water Use in the Near East and North Africa (NENA) Region build on country surveys conducted by the Arab Water Council (AWC). They provide country specific information and conclude with a consensus on minimum and maximum concentrations of key parameters of salt tolerance for crop protection. The guidelines address the importance of irrigation scheduling, leaching for salinity control and drainage, and how for example irrigation management (conventional vs. high frequency irrigation), reclamation leaching, and irrigation methods, including blending, cyclic and sequential reuse, influence this relationship. The guidelines further provide a range of maximum limits depending, for example, upon irrigation management, attainable leaching fractions and expected yield potential, and present related good agricultural practices (FAO & AWC, 2023).

[3] The piece-wise linear model assumes no yield decline until a "salinity threshold" value and a linear decrease in yield beyond the threshold.

[4] See Sonmez *et al.* (2008) for the relation between ECe and EC in 1:1, 1:2 and 1:5 soil-water extracts under Cl- dominated conditions.

Table 5.2. Yield potentials of some grain, forage, vegetable and fibre crops as a function of average root zone salinity

Common name	Tolerance based on	Specified salinity (ECe, dS/m) to achieve 50, 80 and full yield potential[1]		
		50%	80%	100%
Durum wheat	Grain yield	19	11	<6
Barley	Grain yield	18	12	<8
Cotton	Seed cotton yield	17	12	<8
Rye	Grain yield	16	13	<11
Sugar beet	Storage root	16	10	<7
Wheat	Grain yield	13	9	<6
Sorghum	Grain yield	10	8	<7
Alfalfa	Shoot dry weight	9	5	<2
Spinach	Top fresh weight	9	5	<2
Broccoli	Shoot fresh weight	8	5	<3
Egg plant	Fruit yield	8	4	<1
Rice, paddy	Grain yield	7	5	<3
Potato	Tuber yield	7	4	<2
Maize	Ear fresh weight	6	3	<2

[1] These data serve only as a guideline to relative tolerances among crops. Absolute tolerances can vary between varieties also depending on climate, soil conditions and cultural practices.

Source: Based on the salt tolerance data of different crops and the percentage decrease in yield per unit increase in root zone salinity in terms of dS/m as reported by Maas, E.V & Grattan, S.R. 1999. Crop yields as affected by salinity. In R.W. Skaggs & J. van Schilfgaarde, eds. Agricultural drainage, pp. 55–108. Madison, WI, ASA-CSSA-SSSA.

Besides the Maas and Hoffman piece-wise linear function (Equation 4), various non-linear models have been proposed to relate crop yield to salinity (van Genuchten & Hoffman, 1984; Steppuhn *et al.*, 2005). The non-linear response functions for reduction in uptake/transpiration as a function of salinity appear to be more realistic than the linear functions created under controlled laboratory conditions, but these require more data and the exponential expressions are more complex. Under field conditions, distribution of salts is neither uniform with soil depth nor constant with time. The non-uniformity of salinity distribution is usually affected by both irrigation and leaching practices, and by the amount and distribution of rainfall (Minhas *et al.*, 2020).

5.1.2. Sodicity

Sodicity in soil or water is a measure of the relative concentration of sodium (Na) to calcium (Ca) and magnesium (Mg). It causes adverse effects on the physical and chemical properties of soil, such as changes in the ratios of exchangeable cations, the destabilization of soil structure, the deterioration of soil hydraulic properties, and an increase in susceptibility to crusting, runoff, erosion and reduced aeration. In addition, imbalances in mineral nutrition usually occur in plants grown on sodic soils, which may range from deficiencies of several nutrients to high levels of Na (Sumner, 1993; Quirk, 2001). Such chemical and physical changes have a bearing on the activity of plant roots and soil microbes, and ultimately on crop growth and yield.

Sodicity in soils is traditionally expressed in terms of the exchangeable sodium percentage (ESP). A sodic soil, by definition, contains relatively high levels of exchangeable sodium (ExNa) compared to all major exchangeable cations (i.e. calcium, magnesium, potassium and sodium) or cation exchange capacity (CExC). The exchangeable sodium percentage (ESP) is calculated as shown in Equation 5:

$$ESP = (ExNa\ /\ CExC) \times 100 \qquad [5]$$

Commonly the distinction between a saline and a sodic soil is drawn at ESP < 15 saline, and ≥ 15 sodic, unless the electrical conductivity is also high (ECe > 4 dS/m) and the soil is classified as a saline-sodic soil (US Salinity Laboratory Staff, 1954; Estefan *et al.*, 2013). In some countries, such as Australia, soils with ESP > 6 are considered as sodic soils. A possible classification of soil sodicity according to the ESP in Australia is given in Table 5.3.

Table 5.3. Classification of sodic soils under Australian conditions

	Non-Sodic	Sodic	Moderately Sodic	Strongly Sodic	Very Strongly Sodic
ESP (%)	<6	6-10	10-15	15-25	>25

Source: www.terragis.bees.unsw.edu.au/terraGIS_soil/sp_exchangeable_sodium_percentage.html.

Soil dispersion problems may occur at a higher or lower ESP depending upon clay type, soil and irrigation water salinity, and overall chemistry of irrigation water and soil. Possible ranges of ESP associated with a significant yield loss of different crops are shown in Table 5.4.

Table 5.4. Soil ESP ranges indicating about 50% yield loss

ESP range	Crop	
	Common Name	**Botanical Name**
10-15	Safflower Mash Pea Lentil Pigeon Pea Urd bean	*Carthamus tinctorius L.* *Vigna mungo (L.) Hepper* *Pisum sativum L.,* *Lens culinaris Medik.* *Cajanus cajan (L.) Millsp.* *Phaseolus mungo L.*
16-20	Bengal gram Soybean	*Cicer arietinum L.* *Glycine max (L.) Merr.*
20-25	Groundnut Cowpea Onion Pearl millet	*Arachis americana Medik.* *Vigna unguiculata (L.) Walp* *Allium cepa L.* *Pennisetum glaucum (L.) R.Br.*
25-30	Linseed Garlic Guar	*Linum usitatissimum L.* *Allium sativum L.* *Cyamopsis tetragonoloba (L.) Taub.*
30-50	Indian Mustard Wheat Sunflower Guinea grass	*Brassica juncea L. Czern.* *Triticum L.* *Helianthus L.* *Panicum maximus Jacq.*
50-60	Barley Sesbania	*Hordeum vulgare L.* *Sesbania bispinosa (Jacq.) W. Wight*
60-70	Rice Para grass	*Oryza sativa L.* *Brachiaria mutica (Forssk.) Stapf.*
70+	Bermuda grass Kallar/Karnal grass Rhodes grass	*Cynodon dactylon (L.) Pers* *Leptochloa fusca (L.) Kunth* *Chloris gayana Kunth*

Source: After Gupta, R.K. & Abrol, I.P. 1990. Salt-affected soils: Their reclamation and management for crop production. Advances in Soil Science, 11, 223–288.

Sodicity in soil solution or irrigation water is often assessed by estimating the sodium adsorption ratio (SAR), which is expressed in terms of the relative concentrations of Na to that of Ca and Mg. As shown in Equation 6, C represents concentrations in $mmol_c/L$ of the cations denoted by subscript letters (US Salinity Laboratory Staff, 1954).

$$SAR = C_{Na} / [(C_{Ca}+C_{Mg})/2]^{0.5} \qquad [6]$$

While SAR is used widely to evaluate the sodicity hazard in many arid zones of the world (see Table 3.3), it does not capture the complexity of soil chemistry. Research and practice in recent years have demonstrated that potassium (K) and Mg, in addition to Na, can have adverse impacts on the permeability of irrigated soils (Rengasamy & Marchuk, 2011; Smith, Oster & Sposito, 2015; Oster, Sposito & Smith, 2016; Qadir *et al.*, 2021).

Magnesium, for example, may cause deleterious effects on soil structure like those caused by sodium. The possibility of such magnesium effects is particularly important under conditions in which irrigation waters have magnesium-to-calcium ionic concentration ratios > 1 (Vyshpolsky *et al.*, 2008). Long-term use of irrigation water with elevated K concentrations also poses challenges to maintaining good soil structure and adequate infiltration rates (Smith, Oster & Sposito, 2015; Oster, Sposito & Smith, 2016).

Rengasamy & Marchuk (2011) have proposed a different irrigation water quality parameter: the cation ratio of structural stability (CROSS). This includes the dispersive effect of K in addition to that of Na, and differentiates the flocculating effect of Mg from that of Ca (Equation 7).

$$CROSS = (C_{Na} + 0.56C_K) / [(C_{Ca} + 0.60C_{Mg})/2]^{0.5} \qquad [7]$$

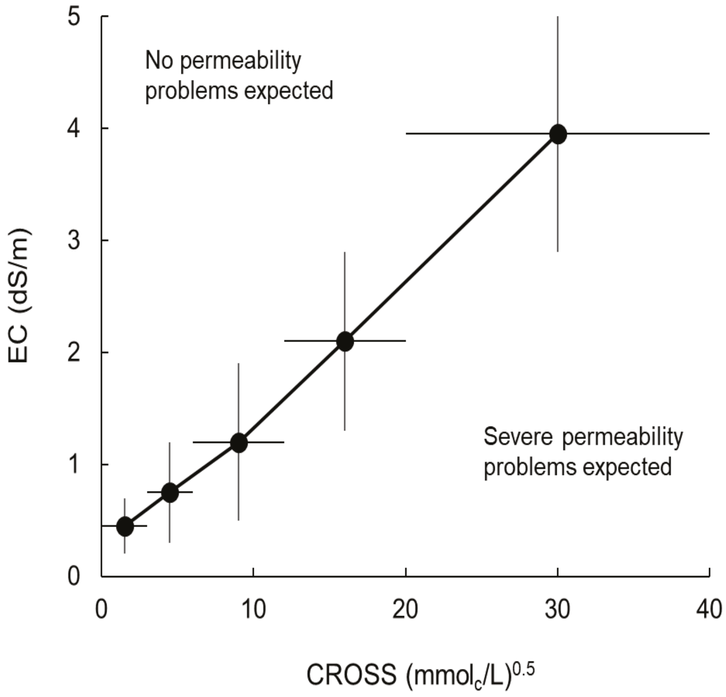
where C represents concentrations in $mmol_c/L$ of the cations. The coefficient of K (0.56) is based on the ratio of the dispersive powers (reciprocal of flocculating powers) of Na and K, and the coefficient of Mg (0.60) is based on the ratio of the flocculating powers of Ca and Mg. However, both coefficients can vary in nature (Qadir *et al.*, 2021). Nevertheless, Equation 7 addresses the over-simplification in Equation 6 (SAR), which treats Mg equal to Ca in terms of flocculating effects. In many waters, Mg concentration is low relative to Ca, although there are well-known exceptions (Oster, Sposito & Smith, 2016).

The principal factor that determines the extent of adverse effects of irrigation sodicity on soil hydraulic properties is the accompanying electrolyte concentration in the soil solution, with low concentrations promoting deleterious effects under sodic environments. Infiltration problems occur due to clay swelling, the breakdown of macroaggregates into microaggregates upon wetting and/or crusting. All these processes result in a reduction in the number and size of large pores at the soil surface, reducing the infiltration of rainfall or irrigation water.

Based on the water quality data of 600 water samples representing arid and semi-arid regions around the world, Qadir *et al.* (2021) proposed revised irrigation water quality guidelines for assessing soil permeability problems (Figure 5.2). These guidelines are intended to cover a wide range of water quality conditions that occur in irrigated areas and apply to whatever combinations of K and Mg are used to calculate CROSS. The use of CROSS in place of SAR is particularly advisable for waters with EC < 4 dS/m, and where the Mg concentration exceeds the one of Ca.

The changes in the permeability of irrigated soils depend on a range of factors, such as soil texture, clay mineralogy, soil depth, presence of compacted layer(s) in the subsoil, the crop(s) to be grown, depth and quality of groundwater, methods and timing of irrigation, provision of a drainage system and its efficiency, rainfall pattern and ambient climatic conditions.

Figure 5.2. Graphic representation of the interpretation of electrical conductivity (EC) and the cation ratio of structural stability (CROSS) to assess soil permeability hazard based on Ayers & Westcot (1985) using EC and SAR.



Source: Qadir, M., Sposito, G., Smith, C.J. & Oster, J.D. 2021. Reassessing irrigation water quality guidelines for sodicity hazard. Agricultural Water Management, 255, 107054.

Another option to express the relationship between sodicity and salinity is the electrochemical stability index (ESI), which is determined by calculating the ratio of the EC of a one-part soil to five parts soil extract (EC1:5 – dS/m) and the exchangeable sodium percentage (ESP). A tentative critical ESI value for Australian cotton soil is 0.05. An economically viable response to gypsum and/or lime can be expected where ESI values are at or below this level (Hulugalle & Finlay, 2003).

5.2.3. Specific ionic effects, toxicities and nutrient imbalances

An excess of macro- or micro-nutrients can occur under saline conditions through over-fertilization and/or the use of wastewater. Depending on its source, treatment and dilution, wastewater can contain nutrients in high concentrations. Its application in combination with fertilizer application can provoke a nutrient imbalance in soils and crops, while boosting biomass production, for example, with a resulting low economic (i.e. grain) yield.

Water quality-related specific ion effects can relate to mineral-nutrition disorders and the toxicity of specific elements. Moreover, some elements such as manganese (above 0.05 mg/L) and iron (above 0.3 mg/L) can clog micro-irrigation equipment, creating a management-related risk of high element concentrations.

With reference to mineral-nutrition disorders, salts in irrigation water may cause extreme ionic ratios in the soil solution and thus can induce nutritional imbalances in crops. The uptake of certain nutrients and their accumulation by plants may decrease because of competitive processes. For example, Na-induced K or Ca deficiencies may develop in crops by excess sodium salts or a reduction in NO_3^- uptake under saline environments dominated by Cl^- salts (Grattan & Grieve, 1999; Corrado *et al.*, 2020).

As wastewater might not be the only source of nutrients, but accompany the use of chemical or organic fertilizers, good agricultural practices must be in place to avoid over-fertilization which can affect crops and the environment (see Chapter 8 on Ecology).

A toxicity problem stemming from specific ion toxicity differs from a salinity problem, which prevents the uptake of specific nutrients, in that it occurs within the plant itself. Toxicity problems occur if certain cations and anions – in saline soils often chloride, sodium or boron – present in the soil or added through irrigation water are taken up by the plant and accumulate in concentrations that are high enough to negatively affect plant growth and cause crop damage or reduced yields. In general, permanent, perennial crops (tree and vine crops) are more sensitive to specific ion toxicities than seasonal or annual crops. The initial damage to sensitive crops usually presents as marginal leaf burn and interveinal chlorosis at relatively low ionic concentrations followed by negative effects on crop growth and yield, particularly if the accumulation increases and the ionic concentrations are high enough to cause crop damage. More tolerant annual crops are usually not sensitive at low concentrations but almost all crops are damaged or completely killed if concentrations are sufficiently high (Ayers & Westcot, 1985).

Aside from salinity-related chloride (Cl), sodium or boron (B) effects, toxicity problems can derive from untreated or partially treated wastewater. The different types and amounts of chemical substances in irrigation water depend on the kind of local industry, and its environmental performance and wastewater treatment process (Rodríguez-Eugenio, McLaughlin & Pennock, 2018). Although heavy industry might be limited to coastal cities in low-income countries, textile or mining industries can represents significant inland sources of heavy metals where wastewater treatment is insufficient or absent.

Like sodium, most annual, non-woody crops are not specifically sensitive to Cl, even at higher concentrations (Grieve, Grattan & Maas, 2012). However, most woody species, as well as strawberry, bean and onion, are susceptible to chloride toxicity, but such sensitivities are largely variety and rootstock dependent. Chloride ions move readily with the soil water, are taken up by the crop via the roots, and then move within the transpiration stream where they accumulate in leaves. And like sodium, susceptibility to Cl toxicity is dependent upon the plant's ability to restrict its translocation from the roots to the shoot. By selecting rootstocks that restrict Cl movement within the plant, Cl toxicity can be avoided or at least delayed. The maximum Cl concentrations permissible in the soil water that do not cause leaf injury in selected fruit crop cultivars and rootstocks are shown in Table 5.5.

Table 5.5. Chloride-tolerance limits (mmol/L) of some fruit-crop rootstocks and cultivars

Crop	Rootstock or cultivar	Maximum permissible Cl^- in soil saturation extract without leaf injury[1]
Rootstocks		
Avocado (Persea americana)	West Indian	7.5
	Guatemalan	6
	Mexican	5
Citrus (Citrus sp.)	Sunki mandarin, grapefruit	25
	Cleopatra mandarin, Rangpur lime	25
	Sampson tangelo, rough lemon	15
	Sour orange, Ponkan mandarin	15
	Citrumelo 4475, trifoliate orange	10
	Cuban shaddock, Calamondin	10
	Sweet orange, Savage citrange	10
	Rusk citrange, Troyer citrange	10
Grape (Vitis sp.)	Salt Creek, 1613-3	40
	Dog ridge	30
Stone fruit (Prunus sp.)	Marianna	25
	Lovell, Shalil	10
	Yunnan, Nemagaurd	7.5
Cultivars		
Berries [2] (Rubus sp.)	Boysenberry	10
	Olallie blackberry	10
	Indian Summer raspberry	5
Grape (Vitis sp.)	Thompson seedless, Perlette	20
	Cardinal, black rose	10
Strawberry (Fragaria sp.)	Lassen	7.5
	Shasta	5

[1] For some crops, these concentrations may exceed the osmotic threshold and cause some yield reduction. Data have been adjusted from the original paper to the saturation extract. Over a wide soil textural range, the saturated water content is about twice the field capacity (FC); in other words, the Cl concentration in the saturation extract is about half of that under FC (Rhoades, 1982)

[2] Data available for one variety of each species only.

Source: Adapted from Grieve, C., Grattan, S. & Maas, E. 2012. Plant salt tolerance. In W.W. Wallender & KK. Tanji, eds. Agricultural salinity assessment and management, Second edition. pp. 405–459. Reston, VI, American Society of Civil Engineers.

Toxicity can also occur from direct absorption of the toxic ions through leaves wetted by overhead sprinklers. Sodium and chloride are the primary ions absorbed through leaves, and toxicity to one or both can present a problem for sensitive crops such as citrus. As concentrations increase in the applied water, damage develops more rapidly and becomes progressively more severe.

Although B is an essential micro-nutrient for crop plants, the concentration range of plant-available boron in the soil solution that is optimal for growth for most crops is very narrow. Above this narrow range toxicity can occur (Grattan *et al.*, 2014). Boron problems originating from irrigation water (> 0.5 mg B/L) are more frequent than those originating in the soil. Boron toxicity can affect nearly all crops but, like salinity, there is a wide range of tolerance among crops (Ayers & Westcot, 1985). Concentrations of boron in reclaimed water originate principally from household detergents and cleansing agents and, provided the concentrations are not too high, they are not expected to cause immediate harm to plants. However, boron may accumulate in the root zone through long-term use of reclaimed wastewater. Table 5.6 contains the boron tolerance limits for various crops adapted from Maas and Grattan (1999). For some crops, threshold values and slope (the percentage yield decrease per unit increase in boron beyond the threshold level) are presented such that estimated yield decline functions can be determined in the same manner as those for salinity (ECe) (see above).

Boron toxicity symptoms occur on either old or young developing tissue depending upon its mobility within the plant (Brown & Shelp, 1997). In boron immobile plants, toxicity symptoms (Figure 5.3) usually occur after boron concentrations in leaf blades exceed 250–300 mg/kg on dry mass basis, but as mentioned, not all sensitive crops accumulate boron in leaf blades. For example, stone fruits – peaches, plums and almonds – and pome fruits – apples, pears and others – are easily damaged by boron in young developing tissue, without accumulating enough boron in the leaf tissue. In such cases, leaf analysis is not a reliable diagnostic test for toxicity. With these crops, boron excess must be confirmed from soil and water analyses, tree symptoms and growth characteristics.

Figure 5.3. Boron injury on the margins of "Kerman" pistachio leaves (B-immobile species)

Source: S.R. Grattan, UC Davis.

Table 5.6. Boron tolerance limits in soil water for agricultural crops and fruits (thresholds based on boron concentration in soil

Crop		Boron tolerance parameters			
Common name	**Botanical name**	**Tolerance based on**	**Threshold† (mg/L)**	**Slope (% per mg/L)**	**Rating‡**
Alfalfa	Medicago sativa L.	Shoot DW	4.0–6.0		T
Apricot	Prunus armeniaca L.	Leaf & stem injury	0.5-0.75		S
Artichoke, globe	Cynara scolymus L.	Laminae DW	2.0–4.0		MT
Artichoke, Jerusalem	Helianthus tuberosus L.	Whole plant DW	0.75–1.0		S
Asparagus	Asparagus officinalis L.	Shoot DW	10.0–15.0		VT
Avocado	Persea americana Mill.	Foliar injury	0.5–0.75		S
Barley	Hordeum vulgare L.	Grain yield	3.4	4.4	MT
Bean, kidney	Phaseolus vulgaris L.	Whole plant DW	0.75–1.0		S
Bean, lima	Phaseolus lunatus L.	Whole plant DW	0.75–1.0		S
Bean, mung	Vigna radiata (L.) R. Wilcz.	Shoot length	0.75–1.0		S
Bean, snap	Phaseolus vulgaris L.	Pod yield	1.0	12	S
Beet, red	Beta vulgaris L.	Root DW	4.0–6.0		T
Blackberry	Rubus sp. L.	Whole plant DW	< 0.5		VS
Bluegrass, Kentucky	Poa pratensis L.	Leaf DW	2.0–4.0		MT
Broccoli	Brassica oleracea L. (Botrytis group).	Head FW	1.0	1.8	MS
Cabbage	Brassica oleracea L. (capitata group)	Whole plant DW	2.0–4.0		MT
Carrot	Daucus carota L.	Root DW	1.0–2.0		MS
Cauliflower	Brassica oleracea L. (Botrytis group)	Curd FW	4.0	1.9	MT
Celery	Apium graveolens L. var. dulce (Mill.) Pers.	Petiole FW	9.8	3.2	VT
Cherry	Prunus avium L.	Whole plant DW	0.5–0.75		S
Clover, sweet	Melilotus indica All.	Whole plant DW	2.0–4.0		MT
Corn	Zea mays L.	Shoot DW	2.0–4.0		MT
Cotton	Gossypium hirsutum L.	Boll DW	6.0–10.0		VT
Cowpea	Vigna unguiculata (L.) Walp.	Seed yield	2.5	12	MT
Cucumber	Cucumis sativus L.	Shoot DW	1.0–2.0		MS
Fig, kadota	Ficus carica L.	Whole plant DW	0.5–0.75		S
Garlic	Allium sativum L.	Bulb yield	4.3	2.7	T
Grape	Vitis vinifera L.	Whole plant DW	0.5–0.75		S
Grapefruit	Citrus x paradisi Macfady.	Foliar injury	0.5–0.75		S
Lemon	Citrus limon (L.) Burm. f.	Foliar injury, Plant DW	< 0.5		VS
Lettuce	Lactuca sativa L.	Head FW	1.3	1.7	MS
Lupine	Lupinus hartwegii Lindl.	Whole plant DW	0.75–1.0		S

Muskmelon	Cucumis melo L. (Reticulatus group)	Shoot DW	2.0–4.0		MT
Mustard	Brassica juncea Coss.	Whole plant DW	2.0–4.0		MT
Oats	Avena sativa L.	Grain (immature) DW	2.0–4.0		MT
Onion	Allium cepa L.	Bulb yield	8.9	1.9	VT
Orange	Citrus sinensis (L.) Osbeck	Foliar injury	0.5–0.75		S
Parsley	Petroselinum crispum Nym.	Whole plant DW	4.0–6.0		TT
Pea	Pisum sativa L.	Whole plant DW	1.0–2.0		MS
Peach	Prunus persica (L.) Batsch.	Whole plant DW	0.5–0.75		S
Peanut	Arachis hypogaea L.	Seed yield	0.75–1.0		S
Pecan	Carya illinoinensis (Wangenh.) C. Koch	Foliar injury	0.5–0.75		S
Pepper, red	Capsicum annuum L.	Fruit yield	1.0–2.0		MS
Persimmon	Diospyros kaki L. f.	Whole plant DW	0.5–0.75		S
Plum	Prunus domestica L.	Leaf and stem injury	0.5–0.75		S
Potato	Solanum tuberosum L.	Tuber DW	1.0–2.0		MS
Radish	Raphanus sativus L.	Root FW	1.0	1.4	MS
Sesame	Sesamum indicum L.	Foliar injury	0.75–1.0		S
Sorghum	Sorghum bicolor (L.) Moench	Grain yield	7.4	4.7	VT
Squash, scallop	Cucurbita pepo L. var melopepo (L.) Alef.	Fruit yield	4.9	9.8	T
Squash, winter	Cucurbita moschata Poir	Fruit yield	1.0	4.3	MS
Squash, zucchini	Cucurbita pepo L. var melopepo (L.) Alef.	Fruit yield	2.7	5.2	MT
Strawberry	Fragaria sp. L.	Whole plant DW	0.75–1.0		S
Sugar beet	Beta vulgaris L.	Storage root FW	4.9	4.1	T
Sunflower	Helianthus annuus L.	Seed yield	0.75–1.0		S
Sweet potato	Ipomoea batatas (L.) Lam.	Root DW	0.75–1.0		S
Tobacco	Nicotiana tabacum L.	Laminae DW	2.0–4.0		MT
Tomato	Lycopersicon lucopersicum (L.) Karst. ex Farw.	Fruit yield	5.7	3.4	T
Turnip	Brassica rapa L. (Rapifera group)	Root DW	2.0–4.0		MT
Vetch, purple	Vicia benghalensis L.	Whole plant DW	4.0–6.0		T
Walnut	Juglans regia L.	Foliar injury	0.5–0.75		S
Wheat	Triticum aestivum L.	Grain yield	0.75–1.0	3.3	S

† Maximum permissible concentration in soil water without yield reduction. Boron tolerances may vary, depending upon climate, soil conditions and crop varieties. DW: dry weight; FW: fresh weight.

‡ The B tolerance ratings are based on the following threshold concentration ranges: < 0.5 mg/L very sensitive (VS), 0.5–1.0 sensitive (S), 1.0–2.0 moderately sensitive (MS), 2.0–4.0 moderately tolerant (MT), 4.0–6.0 tolerant (T), and > 6.0 very tolerant (VT).

Source: Adapted from Grieve, C., Grattan, S. & Maas, E. 2012. Plant salt tolerance. In W.W. Wallender & KK. Tanji, eds. Agricultural salinity assessment and management, Second edition. pp. 405–459. Reston, VI, American Society of Civil Engineers.

5.2. Risks from heavy metals

Many potentially toxic elements are normally present in soils as well as wastewater in small amounts and, hence, are also called trace elements. Those metals with relatively high densities, atomic weights or atomic numbers are also called heavy metals. Some of these heavy metals (Zn, Cu, Fe, Ni) are important micro-nutrients when found in low doses, while others, like mercury (Hg), cadmium (Cd), arsenic (As), chromium (Cr), and lead (Pb), are not, but can be found even in some phosphate and nitrate fertilizers (Rodríguez-Eugenio, McLaughlin & Pennock, 2018).

During wastewater treatment, some of these elements may be (at least partially) removed, but others can persist and could present phytotoxic problems. Wherever irrigation water might be affected by effluent from industrial or mining activities, it is recommended not to use it for food production, unless laboratory analysis can verify its safety, based for example on phytotoxic threshold levels (Table 5.7). The same applies to sewage sludge, which can contain accumulated levels of harmful chemicals, and should not be used for food crops, even if treated for pathogens, unless a detailed risk assessment based on laboratory data is possible (Box 5.2). As different chemical elements have varying mobility in soils, the risk assessments might also vary, for example with soil texture and soil acidity (pH), as indicated in Table 5.7. In contrast to sewage sludge, the risk assessment can be different for septic sludge from on-site sanitation systems.[5]

The recommended maximum concentration (RMC) is based on a water application rate of 10 000 m^3/ha/yr. If the water application rate greatly exceeds this, the maximum concentrations should be adjusted downward accordingly. No adjustment should be made for application rates of less than 10 000 m^3/ha/yr. The values given are for water used on a long-term basis at one site.

RMC levels are established based mainly on concerns about soil protection, as irrigation with contaminated water can lead to long-term accumulation of potentially toxic compounds. However, there are distinct differences in the mobility and bioavailability of heavy metals (trace elements) and thus their risks for crops and humans. They can be divided roughly into four groups depending on their soil retention and translocation within the plant (Table 5.8). In brief, group 1 elements are poorly soluble and hardly taken up by plants; group 2 elements are in part taken up but remain in the roots; group 3 elements accumulate in and kill the plant before the concentration reaches values which can affect humans; and group 4 elements are easily transferred and can accumulate in the plant without damaging it, and thus pose the highest risk for consumers (Chaney, 1980).

Cadmium has been identified as the main heavy metal of concern in wastewater, as compared to other metals it is more available to plants and can be found in the edible parts of crops. Although not usually toxic to plants, it can present great risks to human health. However, as heavy metals can accumulate in soils over long periods, it is necessary to control not only irrigation water but also soils and metal concentrations in the crop. However, permissible limits for heavy metals in soil-plant systems vary significantly for soils based on their characteristics, as well as on the type of crop and sampled crop component (e.g. root, shoot, older/younger leaves, fruit/seeds) over the growing season (Shahid, 2017).

[5] Septic sludge (septage), for example, from backyard septic tanks or pit latrines is considered a safer product than sewage sludge from a chemical perspective, but requires pathogen control (Nikiema, Cofie & Impraim, 2014).

Table 5.7. Recommended maximum concentrations (RMC) of selected metals and metalloids in irrigation water

Element	RMC mg/L	Remarks
Aluminium	5.00	Can cause non-productivity in acid soils (pH < 5.5), but more alkaline soils at pH > 7.0 will precipitate the ion and eliminate any toxicity.
Arsenic	0.10	Toxicity to plants varies from 12 mg/L for Sudan grass to less than 0.05 mg/L for rice, as mobility is higher in flooded soils.
Beryllium	0.10	Toxicity to plants varies widely, ranging from 5 mg/L for kale to 0.5 mg/L for bush beans.
Cadmium	0.01	Toxic at concentrations as low as 0.1 mg/L in nutrient solution for beans, beets and turnips. Conservative limits are recommended due to the risk of accumulation in plants and soils.
Chromium	0.10	Not generally recognized as an essential plant growth element. Conservative limits are recommended.
Cobalt	0.05	Toxic to tomato plants at 0.1 mg/Lin nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Copper	0.20	Toxic to several plants at 0.1 to 1.0 mg/L in nutrient solution.
Iron	5.00	Non-toxic to plants in aerated soils (pH > 5), but can contribute to soil acidification and loss of availability of phosphorus and molybdenum.
Lithium	2.50	Tolerated by most crops up to 5 mg L. Mobile in soil. Toxic to citrus at low concentrations with a recommended limit of < 0.075 mg/L.
Manganese	0.20	Toxic to a number of crops at a few-tenths to a few mg/L in acidic soils (pH < 5).
Molybdenum	0.01	Non-toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high concentrations of available molybdenum.
Nickel	0.20	Toxic to a number of plants at 0.5 to 1.0 mg/L. Reduced toxicity at neutral or alkaline pH.
Lead	5.00	Can inhibit plant cell growth at very high concentrations.
Selenium	0.02	Toxic to plants at low concentrations and toxic to livestock if forage is grown in soils with relatively high levels of selenium.
Zinc	2.00	Toxic to many plants at widely varying concentrations. Reduced toxicity at pH ≥ 6.0 and in fine textured or organic soils.

Source: WHO. 2006. Guidelines for the safe use of wastewater, excreta and greywater. Volume II, Wastewater use in agriculture. WHO-UNEP-FAO, based on Ayers, R.S. & Westcot, D.W. 1985. Water quality for agriculture. FAO Irrigation and Drainage Paper 29, Rev. 1. Rome, FAO, and Pescod, M. 1992. Wastewater treatment and use in agriculture. Irrigation and Drainage Paper No. 47. Rome, FAO.

Table 5.8. Trace elements classified in groups according to their potential risk to the food chain through absorption by soil-plant transfer

Group	Metal	Soil adsorption	Phytotoxicity	Food chain risks
1	Ag, Cr, Sn, Ti, Y and Zr	Low solubility and strong retention in soil	Low as limited or no uptake	Low risks because they are not taken up by plants
2	Hg and Pb	Strongly absorbed by soil colloids	Plant roots may adsorb elements but not translocate them to shoots; generally not phytotoxic except at very high concentrations	Pose minimal risks to human health Risks to grazing animals (or humans) if contaminated soils are ingested
3	B, Cu, Mn, Mo, Ni and Zn	Less strongly absorbed by soil than groups 1 and 2	Readily taken up by plants and phytotoxic at concentrations that pose little risk to human health	Conceptually, the "soil-plant barrier" protects the food chain from these elements
4	As, Cd, Co, Mo, Se and Tl	Least absorbed by the soil of all metals (plant uptake likely)	Pose human or animal health risks to plant tissue concentrations that are not generally phytotoxic	Bioaccumulation through the soil-plant-animal food chain. Soils contaminated with As* or Cd pose the most widespread risks to the food chain.

* Arsenic (As) in groundwater used for drinking is a major health concern in Asia. Continuous build-up of As in the soil through irrigation can affect crop roots and reduce yields. The risk for humans through eating As-exposed crops requires more research (Heikens, 2006). Other sources of As in soils include agrochemical compounds (pesticides, herbicides) and mining and smelting activities.

Source: Rodríguez-Eugenio, N., McLaughlin, M. & Pennock, D. 2018. Soil pollution: A hidden reality. Rome, FAO; based on Chaney, R.L. 1980. Health risks associated with toxic metals in municipal sludges. In G. Bitton *et al.* (eds.) Sludge: Health risks of land application. Ann Arbor, MI, Ann Arbor Science, pp. 59–83

Box 5.2. Heavy metal-related guidelines for sewage sludge application in agriculture

EU Directive 86/278/EEC encourages the use of sewage sludge in agriculture for its nutrient value, but regulates its use to prevent harmful effects on soil, surface and groundwater, plants, animals and people. Sludge should not exceed the values outlined in Table 5.9 (to be analysed at least every six months) and its application should not surpass the concentration defined for selected heavy metals in soils (Table 5.10). To avoid pathogenic risks, the guidelines refer in general to treated sludge (septage and sewage sludge) which has undergone biological, chemical or heat treatment, long-term storage or any other appropriate process, so as to significantly reduce possible health hazards resulting from usage. Under certain conditions, the use of untreated sludge can be permitted if there is no risk to human or animal health, for example if it is injected or worked into the soil. Restrictions may also be less stringent for sludge from small sewage treatment plants which treat primarily domestic waste.

Sludge must not be applied to soil in which fruit and vegetable crops are growing or grown (with the exception of fruit trees), or less than ten months before fruit and vegetable crops are to be harvested. Grazing animals must not be allowed access to grassland or forage land less than three weeks after the application of sludge.

Table 5.9. EC limits for heavy metal concentrations in sludge for use in agriculture (mg/kg of dry matter)

Parameters	Limit values
Cadmium	20 to 40
Copper	1 000 to 1 750
Nickel	300 to 400
Lead	750 to 1 200
Zinc	2 500 to 4 000
Mercury	16 to 25
Chromium (1)	1000

(1) Value from France; the EC did not define a Cr limit as of end 2022

Source: European Commission. 1986. Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture. Official Journal of the European Union, 181, 4.7.1986, pp. 6–12

Table 5.10. EC limits for concentrations of heavy metals in soils with a pH of 6 to 7 (mg/kg of dry matter). Land spreading is not authorized if the soil pH is below 5.

Parameters	Limit values (1)
Cadmium	1 to 3
Copper (2)	50 to 140
Nickel (2)	30 to 75
Lead	50 to 300
Zinc (2)	150 to 300
Mercury	1 to 1.5
Chromium (3)	150

(1) EC member States may permit the limit values they set to be exceeded if e.g. commercial food crops are being grown exclusively for animal consumption, without human or environmental risk.

(2) EC member States may permit the limit values they set to be exceeded by max 50% in respect of these parameters on soil with a pH consistently higher than 7, and no risk in particular for groundwater.

(3) Value from France; The EC did not define a Cr limit as of end 2022.

Source: https://ec.europa.eu/environment/archives/waste/sludge/pdf/sludge_disposal2a.pdf

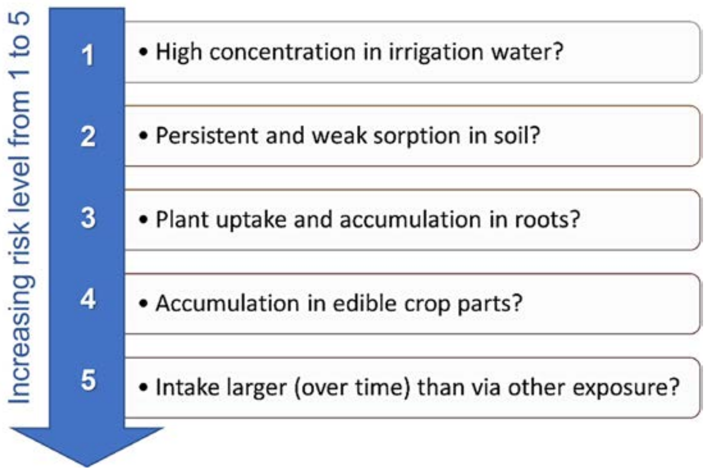
5.3. Risks from organic contaminants of emerging concern (CEC)

A wide range of organic contaminants can be present in industrial or municipal wastewaters, including pesticides, healthcare products, persistent organic pollutants, micro-plastics, pharmaceutical and personal care products, or residues of any of these. These contaminants are commonly referred to collectively as contaminants of emerging concern (CEC). Most are released into the environment as a result of human activities and might not be removed through conventional wastewater treatment. The presence of this type of organic compounds can be of relevance for agricultural wastewater use, although a comprehensive risk assessment for agro-food systems is still limited by multiple factors, not least the sheer number of CEC and their diverse structures and environmental behaviour.

Soil serves as the initial recipient of CEC when agricultural fields are irrigated or amended with biosolids (treated faecal sludge). Sorption to soil and degradation in soil play an important natural role in controlling the availability of CEC for plant uptake. While most of these substances come only in small concentrations, many CEC are taken up by roots. Uptake varies with the physical and chemical properties of the organic contaminant, the biological characteristics of the plant as well as soil physical and chemical characteristics. Once CEC enter plant roots, the chemicals can potentially translocate to different organs where they may be transformed by the plant metabolism. Uptake and accumulation of CEC in edible crops present a potential route for human exposure via dietary ingestion. Based on observations to date, CEC are accumulated in edible fruits, leaves or roots, typically within a very small range. Under field conditions, the estimated dietary consumption of a pharmaceutical by-product, for example, would be several orders of magnitude less than any prescribed daily dose for such a pharmaceutical. However, there is little knowledge pertaining to long-term human health effects, or synergistic effects of the combination of various compounds, and as a result regulatory standards or guidelines are only slowly emerging. In comparison with pathogenic health risks, the presence of organic chemical levels on irrigated vegetables, even if elevated, is considered to be of secondary importance in view of human health in low-income countries (WHO, 2006; Amoah *et al.*, 2006). In comparison, fish grown in CECs polluted water could present a higher human health risk (Meador, Yeh & Gallagher, 2018).

Figure 5.4 summarizes a theoretical flow chart from low to high risk. Access to the required data and information to follow such a guiding framework could be a challenge (Fu *et al.*, 2019).

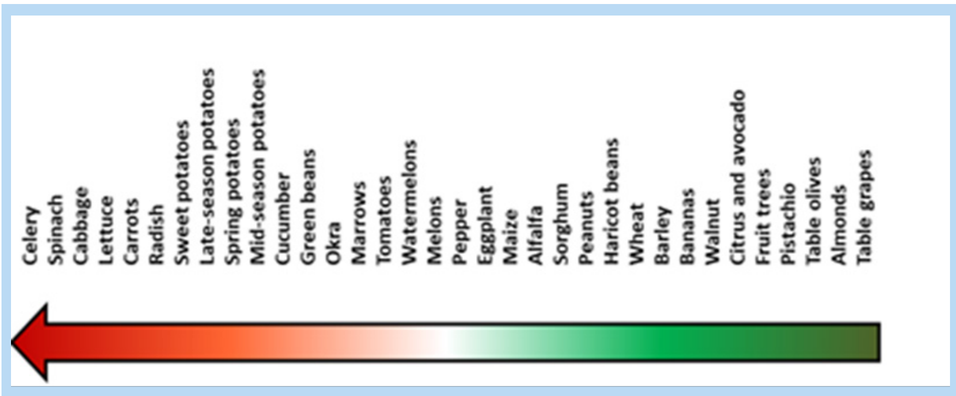
Figure 5.4. Contaminants of emerging concern risk chart



Source: Modified from Fu, Q., Malchi, T., Carter, L.J., Li, H., Gan, J., & Chefetz, B. 2019. Pharmaceutical and Personal Care Products: From Wastewater Treatment into Agro-Food Systems, Environmental Science & Technology 2019 53 (24), 14083-14090

Some guidance on differences between crops in view of their CEC uptake potential is provided in Figure 5.5. In general, crops with a high transpiration rate are expected to have a higher absorption potential for CEC when grown in warm and dry conditions following the order of: Leafy vegetables > root vegetables > cereals and fodder crops > fruit vegetables.

Figure 5.5. Increasing potential of CEC uptake by different plant species



Source: Christou, A., Papadavid, G., Dalias, P., Fotopoulos, V., Michael, C., Bayona, J. M., Piña, B. & Fatta-Kassinos, D. 2019. Ranking of crop plants according to their potential to uptake and accumulate contaminants of emerging concern. Environmental Research, 170, 422–432.

The World Health Organization (WHO, 2006) has published numerical limits to define the maximum permissible concentrations of a selected group of organic contaminants in agricultural soils (Table 5.11). The values relate to the levels at which contaminants can be transferred to humans through the food chain. However, for most of these organic contaminants, the possibility of accumulating in the soil is small due to their typically low concentrations in wastewater.

Table 5.11. Maximum tolerable concentrations of selected pesticides and other organic chemicals in soils exposed to wastewater or treated sludge applications

Contaminant	Soil concentration (mg/kg)	Contaminant	Soil concentration (mg/kg)
Aldrin	0.48	Methoxychlor	4.27
Benzene	0.14	PAHs (as benzo[a]pyrene)	16.00
Chlordane	3.00	PCBs	0.89
Chloroform	0.47	Pentachlorophenol	14.00
2,4-D	0.25	Pyrene	41.00
DDT	1.54	Styrene	0.68
Dichlorobenzene	15.00	2,4,5-T	3.82
Dieldrin	0.17	Tetrachloroethane	1.25
Dioxins	0.00012	Tetrachloroethylene	0.54
Heptachlor	0.18	Toluene	12.00
Hexachlorobenzene	1.40	Toxaphene	0.0013
Lindane	12.00	Trichloroethane	0.68

Source:WHO. 2006. Guidelines for the safe use of wastewater, excreta and greywater. Volume II: Wastewater use in agriculture. Paris, WHO-UNEP-FAO

WHO and FAO have jointly developed the Codex Alimentarius Commission which reviews and updates regularly food safety and quality standards including the maximum residue level of pesticides, heavy metals, and so on in crops based on the acceptable daily intake[6].

5.4. Options for risk reduction

Sustainability of agriculture irrigated with low-quality water will require a comprehensive approach to soil, water and crop management based on risk assessments and risk mitigation. In contrast to the usually invisible risks from pathogens or chemicals in wastewater, farmers are well aware of common salinity problems and receptive to training programs in addressing these challenges. Case study 2 in the annex describes such an example from Bangladesh.

5.4.1. Risk assessments

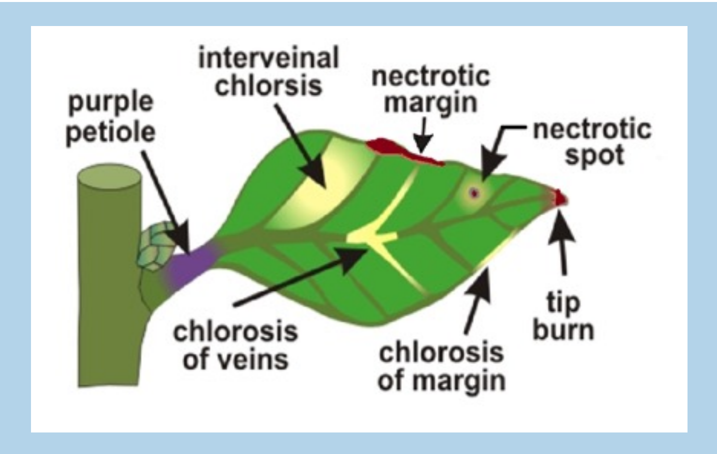
In most cases, risk assessments require a chemical analysis of the irrigation water, the soil and/or the crop, in order to identify pollution or nutritional stress, or imbalances, compared with control sites and local or international standards (see above). Sampling should consider spatial and temporary variability, which will require a variety of samples and separate sample analysis. Comprehensive guidelines for water, soil and plant sampling and analyses have been compiled by Estefan, Sommer & Ryan (2013) among others.

[6] For pesticides, see for example, www.fao.org/fao-who-codexalimentarius/codex-texts/dbs/pestres/pesticides/en

For some abiotic risks, such as salinity, sodicity or specific ion toxicities, laboratory analysis of soils and plant tissue should be accompanied by field observations indicating typical salinity or ion toxicity symptoms (Figure 5.1), or nutritional disorders (Figure 5.3). This is particularly important for situations where no laboratory is available, and visual identification of crop nutrient disorders on crop leaves can provide insights into potential problems (Bergmann, 1992). Field guides, for example, for rice are readily available from the International Rice Research Institute, for wheat from CIMMYT and so on. Online guides in regard to particular nutrient deficiencies are also available for multiple crops from IPI, YARA and others.

Common terms for describing typical foliar symptoms of nutritional disorders are shown in Figure 5.6.

Figure 5.6. Terminology of common leaf abnormalities



Source: http://flairform.com/growers-guide/ (modified)

Risk prevention or mitigation strategies vary with the hazard. In contrast to pathogenic risks (see Chapter 4), which can be addressed through various (low-cost) wastewater treatment processes, and a range of improved water fetching, irrigation, and post-harvest practices (Amoah *et al.*, 2011), the best option for chemical contaminants is risk prevention and tertiary wastewater treatment at source, not mitigation at the farm level (Simmons, Qadir & Drechsel, 2010; Fu *et al.*, 2019). Conversely, for challenges such as salinity, researchers have developed a variety of farm-based options over many decades. Table 5.12 provides a simplified overview and the following sub-sections detail the risk mitigation options, in particular in relation to salinity.

Table 5.12. Options for addressing chemical (non-pathological) threats from low-quality irrigation water

Risk mitigation options / Risks caused by irrigation	Salinity	Sodicity	Boron or Chloride toxicity	Heavy metals	Organic contaminants	Macro-nutrient over-supply
1. Primary and secondary wastewater treatment	Salinity can increase in pond based systems due to evaporation					
2. Tertiary wastewater treatment (reverse osmosis)						
3. Crop/variety restrictions for those capable of withstanding the hazard						
4. Irrigation methods reducing water volume (e.g. drip irrigation, furrows)	Drip clogging possible					
5. Irrigation in excess of crop water requirements to support leaching				Accumulation of less soluble contaminants possible		
6. Irrigation in conjunction with freshwater (cyclic applications, blending)						
7. Good agronomic practices (soil nutrient and water management)				Limited impact if any		
8. Soil amelioration (with limestone, gypsum, etc. to influence soil pH or counter nutrients in excess)						
9. Phytoremediation					To be determined	

Legend: Useful | Very useful

Source: Authors' own elaboration

5.4.2. Crop diversification, restrictions and field trials

A pertinent selection of plant species capable of withstanding ambient levels of salinity and/or sodicity and producing adequate yields is crucially important when using saline, sodic or saline-sodic waters for irrigation. Such restrictions are generally limited to the possibility of access to a replacement crop (or variety) with financially viable market value.

The approach is also applicable to crops able to withstand high levels of boron or chloride, for example. While there exist tables on crop tolerance levels (see Table 5.11), the salt or specific ion tolerance of a crop should be valued in context because optimal selection depends on several soil, crop and climatic factors. The best approach for farmers is to use guidelines such as these to narrow down the choice of crops and then test several on the farm with the available soil and water before making a final selection.

Where the potential for chemical contamination in the area is high (e.g. downstream of a mining, car repair/wash, or an industrial area), and upstream wastewater treatment capacities are unknown or limited, changing food crops to others with lower uptake might not be the safest option, especially where laboratory data are missing. In such cases, a switch to non-food crops is highly recommended, such as forage or bio-energy crops.

The same applies to high salinity. As high-quality forages for cattle and sheep are in short supply in many parts of the world, using salt-tolerant forage grass and shrub species in a forage-livestock system could increase the availability of quality feed, and thus meat and milk outputs. Promising forage species as reported by different researchers include, but are not limited to, Tall wheatgrass, Kallar grass or Australian grass, Para grass, Bermuda grass, Kochia, sesbania, purslane, and shrub species from the genera Atriplex and Maireana (Barrett-Lennard, 2002; Robinson *et al.*, 2003).

The cultivation of bio-energy crops on salt-affected waste lands offers an opportunity to put otherwise unproductive land into production and ensures simultaneously that no natural ecosystems or food-producing agricultural production areas need be converted into systems for renewable energy production. Studies have shown that a range of plant species can be used for renewable energy production on salt-affected environments. Jatropha, toothbrush tree, Russian olive and sweet-stem sorghum are promising examples (Qadir *et al.*, 2010).

Several fruit-tree species have shown promising results under saline environments. Prominent fruit trees for saline environments are date palm, olive, chicle, guava, Indian jujube and karanda (Qureshi & Barrett-Lennard, 1998). Tolerance varies between cultivars but is not the only factor to consider. The water and nutrient requirements of olive, for example, are lower than most other tree species, which represents an advantage in salt-affected areas characterized by low nutrient availability or accessibility to plants.

Studies on establishing rapidly growing tree plantations can offer an opportunity to use salt-affected lands to provide fire wood under saline environment for example, using a variety of indigenous and exotic tree species (Qadir *et al.*, 2008; Qureshi & Barrett-Lennard, 1998). The selection of tree species for salt-affected lands usually depends on the cost of inputs and the subsequent economic and/or on-farm benefits. Planting salt-tolerant nitrogen-fixing trees on salt-affected lands enhances the nitrogen availability and organic matter content in these soils, which are otherwise characterized as deficient of nutrient elements (Kaur, Gupta & Singh, 2002).

5.4.3. Irrigation methods reducing crop exposure to salts

There are different ways to irrigate crops, such as surface or flood irrigation, furrow irrigation, sprinkler irrigation, and micro-irrigation such as drip or trickle irrigation. Table 5.13 presents several parameters for the evaluation of commonly used irrigation methods in relation to the reduction of risks from salts. Some irrigation methods are more suitable for saline water or other types of marginal- or low-quality water than others (Simmons, Qadir & Drechsel, 2010). Drip irrigation systems, for example, have the advantage of reducing the amount of water lost, while decreasing the impacts of salinity. However, clogging of drippers through salt accumulation between emitters may limit the use of drip irrigation systems for saline waters (see chapter 3).

Managing salinity and water stress simultaneously is a complex challenge. Experimental and modelled results regarding leaching efficiency and irrigation frequency can reach contradictory conclusions, depending also on soil and crop characteristics. One often overlooked fact is that salt-stressed plants use less water than non-stressed plants. Thus, irrigating a salt-stressed plant more frequently may not be more beneficial.

Table 5.13. Parameters for evaluating commonly used irrigation methods in relation to risk reduction

Evaluation parameter	Irrigation method			
	Furrow irrigation	Border irrigation	Sprinkler irrigation	Drip irrigation
Foliar wetting and consequent leaf damage resulting in poor yield.	No foliar injury as the crop is planted on the ridge.	Some bottom leaves may be affected but the damage is not so serious as to reduce yield.	Severe leaf damage can occur resulting in significant yield loss.	No foliar injury occurs under this method of irrigation.
Root zone salt accumulation with repeated applications.	Salts tend to accumulate in the ridge which could harm the crop.	Salts move vertically downwards and are not likely to accumulate in the root zone.	Salt movement is downwards, and root zone is not likely to accumulate salts.	Salt movement is radial along the direction of water movement. A salt wedge is formed between drip points.
Ability to maintain high soil water potential (risk of soil moisture stress).	Plants may be subject to stress between irrigations.	Plants may be subject to water stress between irrigations.	Not possible to maintain high soil water potential throughout the growing season.	Possible to maintain high soil water potential throughout the growing season and minimize the effect of salinity.
Suitability to handle brackish wastewater without significant yield loss.	Fair to medium. With good management and drainage acceptable yields are possible.	Fair to medium. Good irrigation and drainage practices can produce acceptable levels of yield.	Poor to fair. Most crops suffer from leaf damage and yield is low.	Excellent/good. Almost all crops can be grown with very little reduction in yield, unless the pipes clog.

Source: Simmons, R.W., Qadir, M. & Drechsel, P. 2010. Farm-based measures for reducing human and environmental health risks from chemical constituents in wastewater. In P. Drechsel et al. (eds.) Wastewater irrigation and health: Assessing and itigating risks in low-income countries, pp. 209–238. London, Earthscan-IDRC-IWMI; after Pescod, M. 1992. Wastewater treatment and use in agriculture. Irrigation and Drainage Paper No. 47. Rome, FAO.

Regardless of how plants respond to integrated stress, they presumably do better when grown on saline soils if water deficit stress is minimized. However, salt-stressed crops might not respond positively to increasing irrigation frequency unless it reduces water stress, maintains the salt concentration in the soil solution below growth-limiting levels, and does not contribute to additional stresses such as oxygen deficit or root disease (Maas & Grattan, 1999).

Several benefits of high frequency irrigation do exist, however, regardless of salinity. These include increased water availability for root uptake, more root activity and improved nutrient management options. Mineral nutrition has been shown to reduce specific toxicity of salts, and thus proper high frequency fertigation could be particularly beneficial for saline conditions (Silber, 2005). Increased frequency is especially favourable for horticultural crops on shallow or coarse-textured soils (Lamm & Trooien, 2003).

5.4.4. Salt management in the root zone

As salts are added to irrigated soils with each irrigation event, it is important to maintain the salinity in the root zone at acceptable levels. Maintenance of salinity can only be achieved by leaching excess salts below the root zone. The leaching frequency depends on the salinity status in water or soil, the salt tolerance of the crop, rainfall and other climatic conditions. Adequate soil drainage is considered as an essential prerequisite to achieve leaching requirement vis-à-vis salinity control in the root zone (Ayars & Tanji, 1999). Natural internal drainage alone may be adequate if there is enough storage capacity in the soil profile, or a permeable subsurface layer occurs that drains to a suitable outlet. An artificial system must be provided if such natural drainage is not present where a perched water table can encroach within the root zone. Besides adequate soil drainage, land levelling and an adequate depth of groundwater are also basic components to maintain salinity in the root zone at a specific level.

If impermeable layers in the soil cause perched water tables that prevent adequate drainage, then drainage water collection systems must be installed and the drainage water disposed of or reused to avoid on-site and off-site salinity effects. To achieve adequate leaching, the volume of irrigation water applied needs to exceed the crop water requirement unless rainfall is adequate to leach excess salts from the root zone.

The leaching requirement (LR) is the minimum leaching fraction needed to control soil salinity to an acceptable level – typically, the full yield potential of the crop. This value varies with both the crop type and the salinity of the irrigation water. The LR can be estimated as follows (Equation 8):

$$LR = ECw / [5 \times (ECe) - (ECw)] \qquad [8]$$

where LR refers to the leaching requirement needed to control the salinity in the root zone within the salt tolerance level of a specific crop by surface irrigation, ECw is the electrical conductivity of applied irrigation water and ECe refers to the average soil salinity (determined from the extract of saturated soil paste) in the root zone that can be tolerated by the crop under consideration (Table 5.2). These values also provide information on yield loss by these crops as the salinity of the soil increases. The identification of the leaching requirement is also important for determining the total water requirement (AW) of the crop (Equation 9; Ayers & Westcot, 1985).

$$AW = ET / (1 - LR) \qquad [9]$$

where AW refers to the depth of applied water per unit area on a yearly or seasonal basis (mm/year or m^3/ha), ET is the annual or seasonal crop water consumption expressed as evapotranspiration (mm/year or m^3/ha) and LR is the leaching requirement expressed as fraction of 1. The leaching required to maintain salt balance in the root zone may be achieved either by applying enough water at each irrigation to meet the LR, or by applying, less frequently, a larger leaching amount sufficient to remove the salts accumulated from previous irrigations.

Guidelines based on such steady-state equations have shown to provide an acceptable approximation, especially in frequently irrigated systems where irrigation is given at a constant ratio to potential crop ET. However, they also tend to overestimate the LR, which can lead to the application of excessive amounts of irrigation water and increased salt loads in drainage systems or underlying aquifers (Corwin & Grattan, 2018).

Furthermore, standard guidelines for managing salinity and irrigation, as described by the equations above, were mostly designed with the goal of maintaining root zone salinity at a level that avoids any reductions in crop growth or yield. However, due to the diminishing availability of good quality water for irrigation, it is increasingly important that irrigation and salinity management tools be able to target at least submaximal crop yields and support the use of marginal quality waters (Skaggs *et al.*, 2014).

More advanced models can serve this purpose and address technical shortcoming by simulating dynamic systems where crop production responds to changing input parameters, including weather conditions or soil hydraulic properties, under consideration of the sensitivity of specific crops to salinity. Such transient state models enable users to relate crop water use and crop yield to dynamic changes in soil salinity and soil water content in the root zone resulting from variations in irrigation water salinity, amounts of applied water, salination due to upward movement of salts from shallow groundwater levels, rainfall and climate.

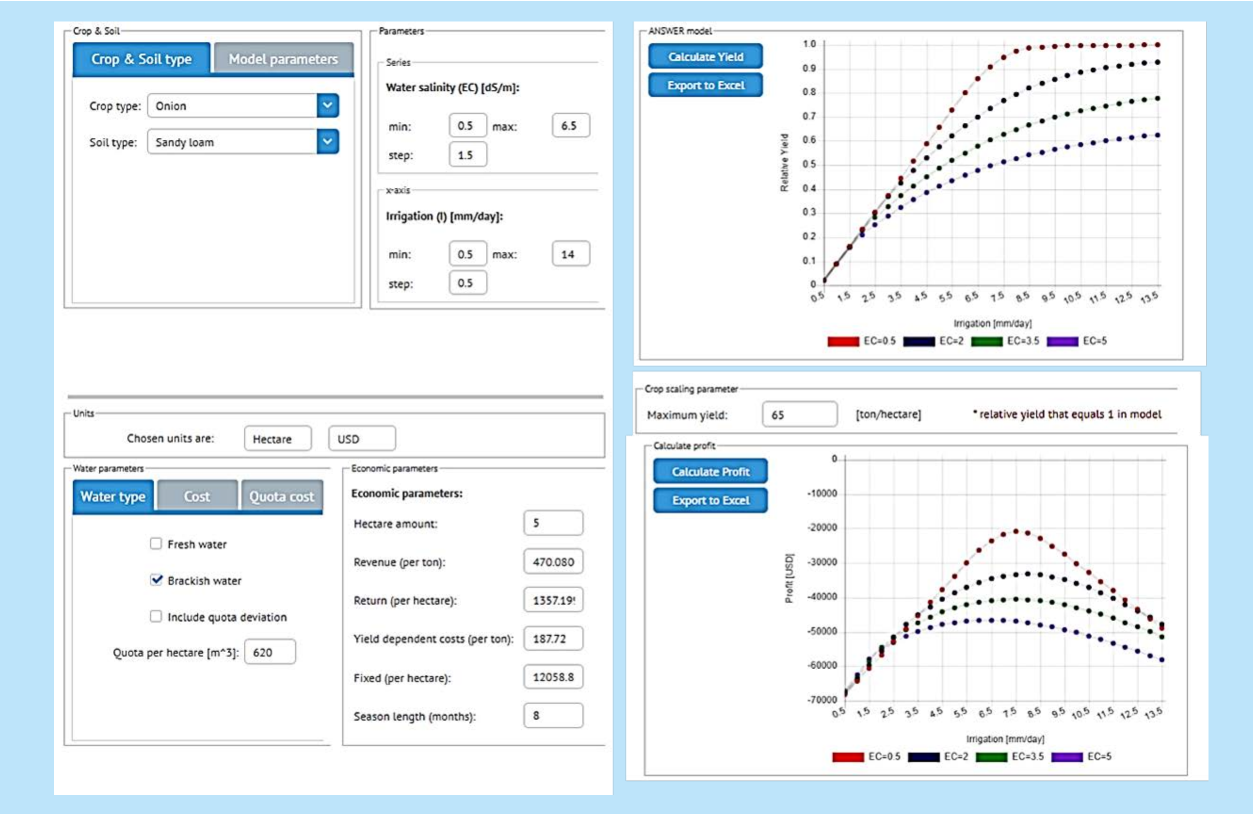
A variety of computer programs and packages developed for modelling water movement in two or three dimensions are freely available and are continuously updated. The popularity of transient state models such as HYDRUS, which serves different irrigation systems under salinity and sodicity, or related models such as STANMOD, RETC, UNSATCHEM and HP1, is growing rapidly, especially in developed countries (Šimůnek, van Genuchten & Šejna, 2016). While able to solve site specific, complex situations, these models are handicapped by the expertise and large number of parameters required for execution (Shani *et al.*, 2007). Further improvements will increase the adaptability of these models to more data-scarce conditions. Until then, the more user-friendly, steady-state models, despite being more conservative than transient models, remain valuable as means to generate a first, quick approximation of the suitability of water for irrigation (Oster *et al.*, 2012). If the water is suitable for irrigation for a particular crop in a particular location, a more rigorous assessment may not be necessary (Corwin & Grattan, 2018).

Less data-intensive models have been presented, for example, by Shani *et al.* (2007, 2009) and Skaggs *et al.* (2014). These "intermediate" models can provide good results as long as irrigation is frequent and regular. The models are easy to use and can calculate plant response to water and salinity, determine LRs and the environmental burden through the quantity of leached salts. Moreover, they can be coupled with a cost-benefit analysis (Figure 5.7) as presented in Kaner *et al.* (2018), or a model implemented by the California State Water Resources Control Board under the framework of the Central Valley Salinity Alternatives for Long-term Sustainability (CV-SALTS) for predicting crop yield and profitability response to saline irrigation water (Nicolas & Kisekka, 2022), based on an analytical approach for steady-state conditions of soil water, plant water uptake and salinity in the root zone (Shani *et al.*, 2007, 2009).

5.4.5. Irrigation in conjunction with freshwater

Saline, sodic and saline-sodic waters can be used for irrigation in conjunction with freshwater (or reclaimed wastewater), if available, through cyclic (temporal alternating) and in-situ blending approaches. Both options are possible: stretching supplies of freshwater by adding saline water, and blending saline water with freshwater. Blending saline waters with good-quality irrigation waters has been a common practice in several water-short regions of Australia, India, Pakistan, Spain and the United States (Tanji and Kielen, 2002; Oster, Sposito & Smith, 2016; Minhas, Qadir & Yadav, 2019). Case study 3 in the annex presents such an example from Spain. Another example of combining water sources to fit different situations is provided in Box 5.3. In all cases, it is important to follow the guidelines for interpretation of the combined effects of salinity and sodicity of blended water used for irrigation on soil physical properties, particularly infiltration rate (Figure 5.2, above).

Figure 5.7. User interface of the ANSWER economic-crop irrigation decision support application



Source: https://app.agri.gov.il/AnswerApp/; Kaner *et al.* (2018), based on Shani *et al.* (2007) analytical soil-water-salinity crop response model.

In an irrigation strategy consisting of cyclic use of saline water and freshwater, the crop rotations may include both moderately salt-sensitive and salt-tolerant crops. Typically, freshwater is used early on to reduce soil salinity in the upper profile, facilitating germination and permitting crops with lesser tolerances to salinity to be included in the rotation. Saline water is used for more salt-tolerant crops or for more salt-sensitive crops later in the season (Minhas, Qadir & Yadav, 2019). The cyclic strategy requires a crop rotation plan that can make best use of the available good quality water and saline water, and considers the different salt sensitivities among the crops grown in the region, including changes in salt sensitivities of crops at different stages of growth.

The advantages of the cyclic strategy include: (i) soil salinity is kept lower over time, especially in the topsoil during seedling establishment; (ii) a broad range of crops, including those with high economic-value and moderate salt sensitivity, can be grown in rotation with salt-tolerant crops; and (iii) conventional irrigation systems can be used. Studies addressing the cyclic use of saline waters (Minhas, Qadir & Yadav, 2019) have shown that this strategy is sustainable for cotton, rice, wheat, safflower, sugar beet, tomato, cantaloupe and pistachio, provided the problems of crusting or poor aeration are dealt with through optimum management.

In the Indian Sub-continent, the soil salinity levels are managed satisfactorily by monsoon rains and the extent of salt leaching depends on the total amount of monsoon rainfall and subsurface drainage. Therefore, problems may arise where there is insufficient rainfall to induce effective leaching. Under such conditions, salinity build-up at the end of the irrigation season may not be ameliorated by rainfall, thus requiring additional water for reclamation leaching.

Box 5.3. Blending of different water qualities in Israel

In Israel, to meet domestic and industrial freshwater demands under limited overall supply, the fraction of natural freshwater used for irrigated agriculture was decreased from about two-thirds (in the 1990s) to currently about one-third. This was accomplished by increasing irrigation water use efficiency and promoting the blending of irrigation water with alternative water sources. Drip irrigation, for example, is used today in Israel at rates higher than anywhere else in the world. The utilization of low-quality water has been encouraged (compensated) through a water for irrigation pricing structure, where the cost to farmers goes down as irrigation water salinity increases. Today, some 60 percent of the irrigation water supply comes from treated wastewater (up to 40 percent) and brackish groundwater. Overall, around 85 percent of all domestic wastewater is reused. However, the salinity levels of the recycled wastewater (between ca. 1 and more than 3 dS/m) and the management of water quality variations can represent a significant burden for the farmer.

Israel's move towards desalination of seawater to ensure national municipal water security has fortunately also reduced the salinity of the recycled wastewater released for irrigation. However, irrigation with pure desalinated water has resulted in crop damage as the reverse osmosis treatment process also removes useful crop nutrients. Thus, the blending of different water sources remains a good strategy, while research is moving towards alternatives to reverse osmosis, in order to selectively remove problematic elements while leaving agricultural desirable crop nutrients in the water (Yermiyahu *et al.*, 2007; Raveh & Ben-Gal, 2015; Tal, 2016; Cohen, Lazarovitch & Gilron, 2018).

5.4.6. Good agronomic practices

Where wastewater treatment is limited, undiluted wastewater might carry a significant nutrient load. This makes crop fertilization and nutrient management a complex task (Janssen *et al.*, 2005) as it requires information on nutrient levels in water, soils and plants. Such data might not be readily available to poor farmers or relevant government departments. Additionally, following strictly local fertilizer application guidelines might not help unless they consider the additional nutrient input from the water. To avoid nutritional disorders, farmers can select crops that are less sensitive to high nutrient levels or which can take advantage of high amounts of P and N. Higher N levels are thus more welcome in farms specializing in leafy crops than fruits or grains. In addition, fodder grass is well suited to absorb N and P applied via wastewater. Where farmers do not have the option to grow crops that benefit from high N or P levels, the irrigation water might first pass through farm-based filter systems to transform part of its nutrient load into biomass. This could take the form of an on-farm pond covered with duckweed (a good fodder) or a wetland system.

5.4.7. Seed placement

Various good agronomic practices exist to mitigate salinity challenges, such as sowing seed on relatively less saline parts of ridges, raising seedlings with freshwater and their subsequent transplanting, mulching of furrows to minimize salinity build-up and maintain soil moisture for longer period, or increasing plant density to compensate for possible decrease in growth.

Since most crops are salt sensitive at the germination/emergence stage, it is important to avoid the use of saline and sodic waters during this critical growth period. Under field conditions, this can be achieved through modification of planting practices to minimize salt accumulation around the seed and improve the stand of crops. For example, double row planting on flat beds can be practised with lettuce, onion, and in certain cases other field crops. Seeds are planted on the edges of the beds where salt accumulation is minimal (Rhoades, 1999). For larger seeded crops, the seeds can be planted in furrows. The seed is placed in a wet and less saline zone, as during the preparation of ridges more saline surface soil goes to the ridges and pre-sowing irrigation helps to leach the salts from furrow soil more efficiently than those of the ridge soil. The beneficial effects of furrow planting in mustard and sorghum over flood irrigation with saline water have been reported (Minhas, Qadir & Yadav, 2019). The practice of furrow planting has also been utilized for creating a favourable environment for the establishment of tree plantations where saline water was the source of irrigation.

Other interventions in addition to planting techniques include pre-sowing irrigation to leach the salts from seeding zone, raising seedlings with freshwater and their transplanting and subsequent irrigations with saline water, the use of mulches to maintain soil moisture for longer periods, and an increase in the seed or seedling rate per unit area (plant density) to compensate for a possible decrease in growth or plant density (Tanji & Kielen, 2002) (e.g. using 25 percent extra seed rate to achieve an expected 10-15 percent improvement in grain yield).

5.4.8. Soil amelioration

Specific soil ameliorants can alter the crop availability of micro-nutrients and heavy metals. Liming with $CaCO_3$, for example, can increase soil pH from 5.5 to 7.0, resulting in a significant reduction in Cadmium uptake among many crops (Gray *et al.*, 1999; Zhu *et al.*, 2016). Other materials, such as organic waste, sawdust or biochar, can absorb heavy metals from irrigation water. A key challenge is to obtain such materials in sufficient quantity and to finance the required laboratory analyses needed to monitor the success of the intervention. Collaborations with universities are recommended if the agricultural extension service has no access to such capacities.

In the case of irrigation with sodic waters or management of soils with a high ESP, there is a need to provide a source of free calcium (Ca^{2+}) to mitigate the effects of sodium and in certain cases of magnesium on soils and crops. Gypsum is the most commonly used source of calcium in this situation, and the amount required can be estimated through simple analytical tests, before being added to the soil or applied with irrigation water. Gypsum application techniques have been refined in the form of "gypsum beds", the use of which improves solubility and application efficiency and reduces the costs of application. Although this method produces significantly higher crop yields than any control, there may be constraints in many developing countries due to (i) the low quality (impurities) of available gypsum; (ii) restricted availability of gypsum in absolute terms or when actually needed; and/or (iii) increased costs due to competing demand (Qadir *et al.*, 2007).

Another low-cost source of calcium is phosphogypsum, which can be used as an amendment for managing high-magnesium waters and soils. Phosphogypsum is a major co-product of the production of fertilizer from phosphate rock. Where phosphate rock is available and mined, phosphogypsum offers additional value as it also supplies some phosphorus and sulfur needed for plant growth (Vyshpolsky *et al.*, 2008). Another calcium-supplying chemical amendment could be calcium chloride, unless chloride-sensitive crops are cultivated on the ameliorated land.

As with contaminants, crop residues, municipal waste compost, manure or biochar can also be useful in ameliorating the effects of soil and irrigation water sodicity. Organic matter left in or added to the field can improve the chemical and physical conditions of the soils irrigated with sodic wastewater by supporting the dissolution of calcite caused by enhanced CO_2 production from microbial breakdown of organic matter (Leogrande & Vitti, 2019).

However, the availability of sufficient quantities of organic material is usually limited in semi-arid climates where salinity problems are most common. Another challenge is the difficulties inherent in recommending an optimal dose of compost or other organic amendments to be applied for saline/sodic soil recovery. Several authors found that successful doses can range from 10 to 50 t/ha of different organic amendments to improve the physical, chemical and biological properties of soils affected by severe problems of salinity and/or sodicity (e.g. ECe > 10 dS/m and/or ESP > 20%). However, high rates of organic amendments (greater than 50 t/ha), even if useful to reduce soil Na content, in many cases increased soluble salt concentrations and provoked the accumulation of undesirable elements (e.g. heavy metals or organic pollutants). This last aspect becomes particularly relevant in coarse-textured soils, characterized by high permeability and low cation exchange capaciity where salts and other organic compounds can be easily leached and may consequently contaminate the subsoil and/or groundwater (Leogrande & Vitti, 2019).

5.4.9. Phytoremediation

Phytoremediation could be a good option for amending soils in developing countries as it is inexpensive and easily scalable. This technique is based on the use of living green plants to fix, adsorb or dissolve contaminants or salts. The application of phytoremediation often remains limited, however, due to the unavailability of suitable plant species, the low biomass production of alternative species and the long growing seasons required.

Phytoremediation might refer to a process internal or external to the plant, namely: the ability of plant roots to absorb particular ions for the plant to accumulate; or chemical changes in the root zone (partial pressure of carbon dioxide increase influencing the dissolution rate of calcite), resulting in enhanced levels of Ca^{2+} in the soil solution to possibly replace Na^+ in the cation exchange complex depending on the respective available amounts (Qadir *et al.*, 2007).

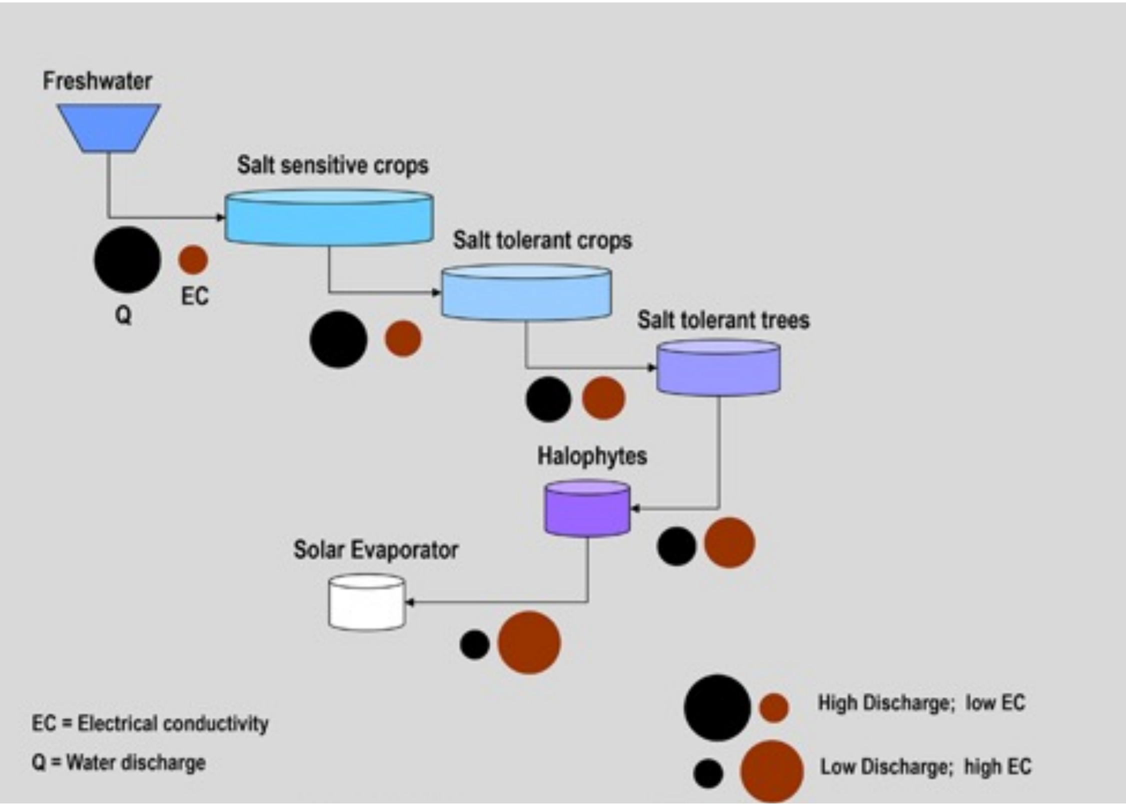
While the first option is more popular in terms of trace elements and some heavy metals (see Chapter 5), the second option can be effective when used on moderately saline sodic and sodic soils if soluble calcite and appropriate plant species are available. However, the efficiency of different plant species used in phytoremediation of sodic and saline-sodic soils has been found to be highly variable. In general, phytoremediation appears to work on moderately sodic and saline-sodic soils, provided: (i) irrigation is performed in excess of the crop water requirement to facilitate adequate leaching, and (ii) the excess irrigation was applied when the crop growth, and hence the partial pressures of carbon dioxide, were at their peak. On such soils, the performance of phytoremediation (e.g. with Para grass or Sesbania) was comparable with soil application of gypsum. On highly sodic and saline-sodic soils, use of chemical amendment is likely to outperform phytoremediation treatments (Qadir *et al.*, 2007).

5.4.10. Off-site salinity management

When setting-up drainage systems, it is essential to consider the possible impacts of the drainage waters on agricultural fields downstream as well as the environment. Thus, it is important to evaluate the suitability of the potential disposal site(s) for the drainage water and the salt it contains.

Two generic options for local management of saline drainage waters are (i) disposal to evaporation basins for regional storage, and (ii) reuse for irrigation of crops able to withstand the levels of salinity and sodicity in the drainage water and its receiving soils (Grattan *et al.*, 2014). The first option represents a missed opportunity to productively utilize saline drainage waters, and such an approach should only be considered where the productive use of these waters is deemed to be economically unsuitable (Qadir *et al.*, 2015). With the second option, the reuse of drainage water to directly irrigate downstream crops (Figure 5.8) by traditional irrigation methods is less sustainable than the original irrigation water as the drainage water contains higher concentrations of salts than the applied irrigation water. Thus, an irrigation cascade relying on drainage water, requires on all steps over-irrigation with the final plants to be likely halophytes (UN Water, 2020). Although sequential reuse is conceptually attractive, caution is advised for those estimating the rate of salt movement through the sequential system, particularly if steady-state assumptions are used (Grattan *et al.*, 2014). See also case study 4 from California in the annex.

Figure 5.8. Schematic representation of a sequential drainage water reuse system



Source: UN Water. 2020. Analytical brief on unconventional water resources. Geneva.

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Chapter 6

Water quality and aquaculture

Philip Amoah and Pay Drechsel

Water quality is very important in fish farming as poor-quality water can affect the health and growth of the fish. On the other hand, fish farming can also significantly affect water quality. Both components will be addressed in this section.

The most effective and reliable means to minimize possible contamination of fish is to harvest from areas with good water quality. In terms of best practice, authorities should therefore encourage, promote and strive to maintain excellence in regard to water quality in fish production areas (Lees, Younger & Dore, 2010). Unfortunately, worldwide degradation of freshwater and marine environments caused by discharges from human settlements and agricultural activities has led to a shortage of pristine environments suitable for aquaculture, highlighting the need for guidelines such as these.

Water quality plays a particularly important role in freshwater aquaculture with the ability to both support and undermine the production of fish and aquatic crops. For farmers, low water quality is a condition to avoid or manage where there is no alternative, or may also constitute a choice. For example, farmers might consciously seek nutrient-rich water that can feed fish and save on operational expenditure. In most situations, however, proximity to urban markets makes peri-urban areas both hotspots for aquaculture initiatives and areas prone to pollution and competition for land and safe water.

Particular support is needed for those enterprises where wastewater is affecting lakes, lagoons, deltas or other wetlands used for farming (Table 6.1). In such natural but highly polluted systems, farmers might target areas closer to the wastewater inflow given the strong positive correlation between organic load, savings on fish feed and high fish growth (Mukherjee & Dutta, 2016).

The most conscious selection of wastewater for farming fish or aquatic plants is the cultivation of fish or crops in waste stabilization ponds (WSPs) of wastewater treatment systems, where farming usually takes place in the last of a system of interconnected treatment ponds. These "maturation" ponds contain the most "treated" water (Table 6.2).

The fish species commonly cultivated in aquaculture systems with low water quality consist of different varieties of carp, catfish and tilapia. The main aquatic plants are lotus, water mimosa, water cress and water spinach, which are used, for example, as traditional medicine or as vegetables for human consumption, or as feed for fish or poultry (in the case of duckweed). Through their ability to transform nutrients into biomass, aquatic macrophytes can contribute significantly to wastewater treatment (Edwards, 1990; Pescod, 1992; WHO, 2006).

Table 6.1. Common water quality affected systems used for fish or aquatic plant production

Fish farm location	Brief description of the aquaculture system	Source
Lakes in urban vicinity serving as natural treatment systems (mostly unplanned)	Water bodies such as Beung Cheung Ek Lake near Phnom Penh, Cambodia, receive largely untreated wastewater from the city. The lake employs biological treatment of wastewater, recapturing nitrogen (N) and phosphorus (P) to produce aquatic vegetables such as morning glory (water spinach) for human and animal consumption.	Kuong, Little & Leschen (2006) Leschen (2018)
Wastewater drains and irrigation channels, paddy fields and farmer-made ponds	Treated and untreated wastewater are directed through a network of channels. Three systems have been observed in Hanoi: (i) fish culture alone, (ii) fish-rice rotations, and (iii) fish-rice-vegetable rotations. In Ho Chi Minh City, a network of smaller, less-defined wastewater channels support the growth of different aquatic plants for human or animal consumption, as well as ornamental fish and fish for consumption.	Minh Phan & Van de Pauw (2005); Hung and Huy (2005); Tuan & Trac (1990)
Wastewater-fed wetlands which function as treatment systems	Natural wastewater-fed ponds and lagoons receive diluted or raw wastewater from the city for treatment. Wetland ponds are usually large and can be 40–50 ha in size. The 12 500 ha of wastewater-fed wetlands in Calcutta, India, are considered the world's largest operational system for the culture of fish in ponds or cages.	Leschen (2018) Leschen, Little & Bunting (2005) Mukherjee & Dutta (2016)
River deltas	Deltas encompass a large variety of aquaculture, including coastal fisheries, brackish water aquaculture (e.g. shrimp farms) and riverside prawn collection. Other systems combine aquaculture with rice production and/or animal husbandry. Water quality is affected by upstream pollution, saline water intrusion and agricultural intensification (including impacts from pond effluent). Examples include the Nile, Mekong, Indus and Ganges deltas.	Oczkowski & Nixon (2008) Nguyen (2017) SourceTrace (2018)

Source: Authors' own elaboration.

Table 6.2. WSP-based fish and fish feed production systems

Production target	Brief description	Source
Fish farming	Fish cultivation in the maturation ponds of the WSP system	Amoah, Gebrezgabher & Drechsel (2021)
Fish farming and irrigation	Fish production within the [facultative and] maturation ponds; treated effluent used for crop irrigation	Kumar *et al.* (2015)
Broodstock production for external fish (and crop farming)	Broodstock cultivation in the maturation ponds of the system; while fingerlings and fish for sale are grown in clean water tanks. Crops are cultivated with wastewater from the fish tanks.	Amoah, Gebrezgabher & Drechsel (2021)
Aquatic plants to feed externally cultivated fish	Aquatic plants grown within the ponds, absorb nutrients, and are either sold or used internally (e.g. as fish feed for fish grown in separate (clean water) ponds or ponds using treated wastewater).	Drechsel *et al.* (2018); Amoah, Gebrezgabher & Drechsel (2021); FAO (1998)

Source: Authors' own elaboration.

6.1. Managing water quality

The key objectives of water quality management are to provide fish with the best possible living conditions, consumers with a safe product and the environment with a well-treated final effluent. All three targets are interlinked as water quality affects feed efficiency, growth rates, fish health and survival, and requires a well-managed integrated system (Kumar & Sierp, 2003; Mara, 2004; Isyagi *et al.*, 2009).

In successful and high-yielding aquaculture systems, farmers work to achieve the maximum standing stock of fish (pond carrying capacity) through balancing an optimal supply of food with an optimal level of oxygen, while minimizing the build-up of toxic metabolic products. Fish mortality in a pond that receives raw or diluted wastewater can result from (i) depletion of oxygen due to an increase in organic load (feed and fish excreta); (ii) depletion of oxygen due to the respiratory demand of a high concentration of phytoplankton caused by an increase in inorganic nutrients; and (iii) a high ammonia concentration due to accumulation of waste (Pescod, 1992).

A wide range of yields have been reported from waste-fed aquaculture systems ranging from: 2–6 t/ha/yr in Indonesia to 2.7–9.3 t/ha/yr in China and 3.5–7.8 t/ha/yr in Taiwan. Management of fish ponds can have a significant effect on fish yields, but in practice the maximum attainable yield is 10–12 t/ha/yr even with energy-rich supplementary feed (Edwards, 1990; Pescod, 1992).

The key water quality parameters for pond production are temperature, oxygen, pH, alkalinity, hardness and certain nutrient levels. Ammonia, for example, can be directly toxic to fish (the fish's own excretion of ammonia is impaired) or support the growth of toxin-producing cyanobacteria (Isyagi *et al.*, 2009; WHO, 2006). Crucially, different species can have different water quality requirements, while the concentrations of many parameters vary with changes in temperature, salinity, hardness, pH and stocking density, among others. Dissolved oxygen (DO) is a common example of a factor that can vary significantly with temperature, species, age or life stage (eggs, larvae, adults) and life process (feeding, growth, reproduction). Several fish cultured in waste-fed ponds appear to be able to tolerate very low DO concentrations for at least short periods of time. African catfish, for example, have accessory organs that enable them to breathe atmospheric oxygen and thus better survive in water at low oxygen levels for short periods. However, this ability does not apply to juvenile catfish, which depend on dissolved oxygen in the water (Isyagi *et al.*, 2009). In other words, an oxygen deficit might not affect the survival of adult fish but would prevent its reproduction. Thus, before stocking fish in a treated wastewater pond, fingerlings should be raised in clean water to the required size (for catfish about 50 g) to achieve a survival rate of 80-90 percent (Isyagi *et al.*, 2009). Air-breathing catfish such as *Clarias batrachus* and *Pangasius bocourti* are followed in decreasing order of tolerance by tilapia, carps and trout. A wastewater fertilized aquaculture system might therefore occasionally require a stand-by mechanical oxygenation system for use during periods when DO would otherwise be very low (Pescod, 1992).

Table 6.3 presents the desirable water quality values recommended by various sources for fish farming. Fish can survive within a wide range, but certain values affect growth or reproduction. Tilapia, for example, can tolerate a pH from 3.7 to 10.5, but below pH 5, they become stressed and will not eat (WRC, 2010).

Table 6.3. Desirable water quality ranges for wastewater-fed aquaculture (warm water species)

Sources	Kaul *et al.* (2002) (India)	Isyagi *et al.* (2009) (Uganda)	PHILMINAQ (2008) (Philippines)	Asmah *et al.* (2016) (Ghana)	BC MOE (2019) (Canada)	DWAF (1996) (South Africa)
pH (comfort zone)	7.5–8.5	6.5–9.0	6.5–9.0	6.5–9.0	6.5–9.0	6.5–9.0
Temperature (°C)	26–33	26 32		22–38		28–30
Dissolved oxygen (DO) (mg/L)	3–10	>4	≥5	3.7–9.0	5–11	5–8
Alkalinity (mg/L) as $CaCO_3$		>20	>20–100	54–200	>20	20–100
Ammonia-nitrogen (mg/L)	<0.25	0.3		<0.5	0.1–1.2*	0–0.3
Dissolved reactive phosphate (mg/L)			0.05–0.1	<1.5		<0.1

* Depending on pH (pH 6.5: 1.2 mg/L; pH 9.0: 0.1 mg/L; for 200C)

Source: Authors' own elaboration.

When fish are cultivated in wastewater treatment systems, the twofold objective of optimizing water treatment and fish production can present a challenge. While a high organic loading will reduce DO and limit the number of fish species that can be cultivated, a low organic loading can result in a correspondingly low level of nutrients for growing phytoplankton – the main source of natural food in fish ponds, and therefore one which represents savings in fish feed (Kaul *et al.*, 2002). Mara (2004) provides design options for wastewater-fed fishponds based on the concept of "minimal treatment for maximal production of microbiologically safe fish".

Locally appropriate fish species can be selected based on their availability and the characteristics of the treated wastewater. African Catfish (*Clarias gariepinus*), for example, is very adaptive to environmental conditions, as found in WSPs, and can live in a wide range of pH and low levels of dissolved oxygen. Species like tilapia, carp, and prawn, on the other hand, would require artificial aeration, like reported from China, India and Viet Nam. Thus, water quality also depends on pond management. Mismanagement will hinder the success of treated wastewater aquaculture systems and can even lead to failure. Many water quality parameters fluctuate daily due to pond dynamics, which include local weather (temperature) conditions, the photosynthetic activities of aquatic plants and so on.

In view of the chemical risks for fish and the food chain, the general recommendation is that industrial effluents should be avoided, or at least be pre-treated within the industry, to remove chemicals likely to enter the same streams as municipal wastewater. Both courses of action are, however, seldom possible in many low-income countries. Thus, where water might contain industrial effluent with potentially toxic chemicals (Table 6.4), bioaccumulation is possible and its use in fish farming is discouraged. However, different chemicals present different levels of risk.

In WSPs, most heavy metals are precipitated under the anaerobic conditions in the first WSP or lose solubility under increasing pH in the maturation pond(s). Algae can accumulate various heavy metals, but fish raised in sewage-fed ponds have not been observed to accumulate high concentrations of possible toxic substances with the possible exception of mercury (Pescod, 1992). One reason is that fish are usually harvested young, and any possible bio-accumulation of toxic metals remains limited. Consequently, the risks from most heavy metals for human health from fish raised in sewage-fed waste stabilization ponds has been assessed as low (WHO, 2006), similar to consumption risks from pesticides or antibiotics even in high-input aquaculture (Murk, Rietjens & Bush, 2018).

Table 6.4. General acceptable levels of selected heavy metals for freshwater environments

Country	Freshwater (µg/L)			
	Hg	Pb	Cd	Ni
Australia	<1.0	<1-7.0	<0.2-1.8	<100
Kenya	5.0	10	10	300
New Zealand	<1.0	<1-7	>0.2-1.8	<100
Philippines	2.0	50	10	NA

Source:PHILMINAQ. 2008. Water quality criteria and standards for freshwater and marine aquaculture (www.aquaculture.asia/files/PMNQ%20WQ%20standard%202.pdf).

In the case of mercury, the fraction of methylmercury (MeHg) poses the most harm, and the threshold for the commonly analysed total Hg amount has to be adjusted when the MeHg share increases. As an example, in the Canadian Guidelines from British Colombia, the average concentration of total mercury should not exceed 0.02 µg/L (20 ng/L) when the MeHg fraction is ≤0.5 percent of the total mercury concentration. When the share of MeHg is greater than 0.5 percent, the guideline should be stricter (see Table 6.5) in order to prevent undesirable levels of mercury in water from entering the food chain where they would pose a threat to sensitive consumers of aquatic life, especially avian species, i.e. birds (BC MoE, 2001).

Table 6.5. Guideline for total Hg as a function of the percentage of methylmercury

% MeHg (of total Hg)	Guideline (ng/L total Hg)
0.5	20.0
1.0	10.0
2.5	4.0
5.0	2.0
8.0	1.25

Source: BC MOE. 2019. British Columbia approved water quality guidelines: Aquatic life, wildlife & agriculture. Summary report. Victoria, BC, British Columbia Ministry of Environment & Climate Change Strategy, Water Protection & Sustainability Branch

In view of the human health risks from fish farming, priority attention should be given to pathogens, in particular food-borne trematodes and schistosomes (Table 6.6), which are endemic in certain geographic regions. Food-borne trematodes present risks where fish is eaten raw or undercooked, while schistosomiasis (bilharzia) is transmitted through water-skin contact where snail hosts are present in aquaculture ponds.

Concentrations of bacteria are always high in the gut of fish, but relatively seldom in the flesh to be consumed. Cross-contamination from gut contents to edible flesh is rare, but can happen during fish cutting and cleaning. Hygienic processing and cooking reduces such risks.

Table 6.6. Microbiological quality targets for wastewater and excreta use in aquaculture

Media	Viable trematode eggs (number per 100 ml or per gram of dry excreta)	*E. coli* (arithmetic mean per 100 ml or per gram of dry excreta)	Helminth eggs (arithmetic mean per litre or per gram of dry excreta)
Product consumers			
Pond water	Not detectable	$<10^4$	<1
Wastewater	Not detectable	$<10^5$	<1
Treated excreta	Not detectable	$<10^6$	<1
Edible fish flesh or plant parts	Infective metacercariae* not detectable or non-infective	Codex Alimentarius Commission HACCP specifications	Not detectable
Aquaculture workers and local communities			
Pond water	Not detectable	$<10^3$	<1
Wastewater	Not detectable	$<10^4$	<1
Treated excreta	Not detectable	$<10^5$	<1

* The final larval form of a trematode

Source: WHO. 2006. Guidelines for the safe use of wastewater, greywater and excreta in agriculture and aquaculture. Volume III: Wastewater and excreta use in aquaculture. Geneva, World Health Organization.

6.2. Human health risk mitigation

The measures which can be taken to protect health in aquacultural use of wastewater are the same as for agricultural use, namely wastewater treatment, crop/fish restrictions, control of wastewater application, human exposure control and promotion of hygiene. For a sustainable wastewater-fed aquaculture business, the risk of pathogens in general and trematode infections in particular should be prioritized to safeguard human health.

Hazard identification, risk assessment and monitoring and/or control of hazards are important steps in ensuring that the health hazards associated with waste-fed aquaculture are identified in a timely manner and addressed to minimize health risks. Monitoring has three different purposes: validation, or proving that the system is capable of meeting its designed requirements; operational monitoring, which provides information regarding the functioning of individual components of the health protection measures; and verification, which usually takes place at the end of the process to ensure that the system is achieving the specified targets (WHO, 2006). The three functions of monitoring are each employed for different purposes at different times:

- Validation is performed when a new system is developed or when new processes are added, and is used to test or prove that the system is capable of meeting the specified targets.
- Operational monitoring is used on a routine basis to indicate that the processes are working as expected. The process relies on compliance monitoring and simple measurements that can be easily read ensuring that decisions can be made in good time to remedy a problem.
- Verification is employed to show that the end product (e.g., treated wastewater/excreta/pond water, fish or plants) meets treatment targets (e.g., microbial reduction targets) and, reduction targets) and, ultimately, health-based targets. Information from verification monitoring is collected on a periodic basis.

As pathogenic hazards also can occur along the whole food chain, WHO's Sanitation Safety Planning (SSP) manual helps to coordinate stakeholders across the sanitation system and prioritizes improvements and system monitoring based on health risks, including those related to wastewater use in agriculture and aquaculture. The SSP manual (WHO, 2022) is targeted primarily at local-level authorities and can also assist regulators, wastewater utilities, sanitation-based enterprises, community-based organizations, farmer associations and NGOs in implementing a multi-barrier approach for risk reduction, which builds on a Hazard Analysis and Critical Control Point (HACCP) system (WHO, 2006).

There are two key risk groups. Firstly, the quality of water is of paramount importance for the protection of workers in waste-fed aquaculture. As the exact water quality might not be known or vary, farm workers should receive training on all the types of risks associated with wastewater-fed aquaculture. Measures must also be put in place to minimize these risks, including protective clothing, options to bathe, and optimize personal hygiene and medical treatment, or regular prophylaxis in proven endemic areas. Transmission of trematode infections can be prevented only by ensuring that no eggs enter the pond or snail control. Similar considerations apply to the control of schistosomiasis in areas where this disease is endemic. As aquatic snails serve as intermediate hosts for Schistosoma, snail monitoring and environmental snail control (e.g., removing vegetation from ponds and their surroundings) are important safety options. According to WHO (2006), the appropriate helminth quality guideline for all aquacultural wastewater use is ≤1 helminth egg per litre.

The second key risk group is consumers. Here, the key question from a pathogenic risk perspective is whether the selected fish will be cooked or eaten raw (or insufficiently cooked). If well cooked, the pathogenic risk of consumption is very low and there should be no objection to the water source if chemical hazards are unlikely (FAO & WHO, 2019). In all other cases, further risk reduction measures are needed, in particular between "farm and fork". This applies in principle also to fish grown in clean water, as contamination can also occur in markets, fish shops or kitchens. Implementing such a multi-barrier system reduces the pressure on farmers to seek perfectly clean water, which is in many regions simply not feasible. The main risk reduction measures are as follows:

- The first additional step at the fish farm is fish depuration preceding harvesting. This involves the placement of batches of living fish in clean water ponds (for at least two to three weeks) after being taken from the treated wastewater-fed ponds, to allow for the external and internal removal of biological contaminants, odour and physical impurities. The depuration ponds should have a flow-through system with the water changed regularly. Relatively short depuration periods of one to two weeks do not appear to remove bacteria from the fish digestive tract. Depuration has shown to be effective for removing sewage-associated bacteria for shellfish, but not satisfactory for the removal of viruses (Lees, Younger & Dore, 2010).
- Fish smoking can contribute to pathogen removal (Yeboah-Agyepong *et al.*, 2019) and also add value after the fish leaves the farm. There are two main methods – cold smoking and hot smoking. The temperature for cold smoking is generally in the range of 30–40°C, while hot smoking is higher at 80–90°C. Almost all microbes except some pathogenic bacteria are destroyed during hot smoking as the higher temperature cooks and completely dries the fish.

- Fish gutting is a key safety step in markets or kitchens. After rinsing the harvested fish under running tap water, the intact gut of the fish is removed, and the cavity rinsed with safe water before removal of the fish muscle. This sequence avoids cross-contamination between the flesh and the contents of the gut. It is very important to use a different knife to cut the flesh after removing the gut contents. Knives used to process the raw fish should not be used for other purposes such as cutting cooked fish or vegetables.
- Depending on public perception, several options exist that will reduce health risks considerably while maintaining the advantage of nutrient-rich wastewater. These options involve a change in business model, specifically either a change in the cultivated fish or the cultivation target, but also depend on access to an alternative (safe) water source such as groundwater. The main options (Amoah, Gebrezgabher & Drechsel, 2021) include:
    - a shift to another fish species which is not consumed raw, but instead cooked, smoked or grilled;
    - growing only fingerlings in the treated wastewater but adult fish without wastewater, a process that results in significantly less contamination (precautions must be taken to prevent trematode infection because trematodes remain viable as long as the host is alive);
    - growing only broodstock with wastewater from which eggs are extracted for the production of fingerlings, which are then cultured in clean groundwater (the process minimizes hazards associated with the final product as the fingerlings do not have direct contact with the treated wastewater);
    - the production of fish feed such as fast-growing duckweed in the ponds, which transform the nutrient load of the wastewater into protein-rich biomass, while fish is cultivated in safer water outside the WSP system.

Case study 5 in the annex presents a related empirical example realized in a public private partnership in Kumasi, Ghana.

It is important to add that only training of fish farmers or kitchen staff might not result in the adoption of any recommended practices and that e.g., incentives might be needed to facilitate behaviour change (Drechsel, Qadir & Galibourg, 2022).

6.3. Environmental risks and risk mitigation

Aquaculture can contribute significantly to the pollution of the aquatic environment at various stages including pond construction, pond treatment, water intake, stocking, nursing, water exchange, sludge discharge, harvesting and pond emptying. This section highlights problematic farming practices from a pollution perspective using the examples of Pangasius and shrimp farming in Viet Nam (Nguyen, 2017), and also explores the opportunities that integrated rice-fish farming offer (Box 6.1).

Box 6.1. Integrated crop-fish systems and water quality

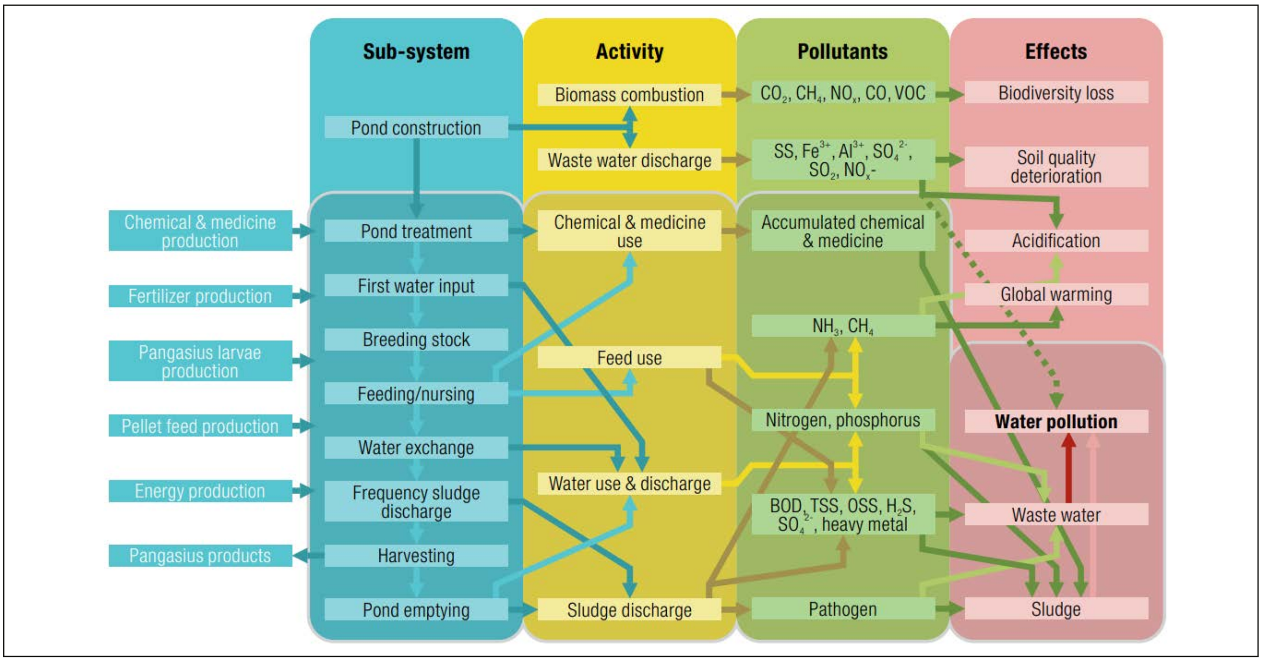
Irrigated rice schemes often involve the cultivation of fish in an upstream irrigation tank (reservoir); however, opportunities may exist for an integrated rice-fish culture in which fish live directly in the rice fields. Although this process requires careful water quality management, it presents significant onsite and offsite benefits.

Promoting integrated fish-crop systems in which fish waste serves as a fertilizer for the crops can be a cost-effective way of minimizing water pollution at the system level. Integrated aquaculture-agriculture (IAA) can also limit pesticides use. A field survey in China demonstrated that although rice yield and rice-yield stability are similar in rice-fish (RF) systems and rice monoculture (RM), RF requires 68 percent less pesticide and 24 percent less chemical fertilizer than RM. A field experiment confirmed this result: fish reduce rice pests and rice favours fish by moderating the water environment. The results also indicate a complementary use of nitrogen (N) between rice and fish in RF, resulting in low N fertilizer application and low N release into the environment (Xie *et al.*, 2011). A study in Myanmar's Ayeyarwady delta showed no impact on paddy yields but a 25 percent increase in economic returns for the same land area from fish in addition to multiple nutritional benefits (Dubois *et al.*, 2019). Studies from Bangladesh and Viet Nam also demonstrated that rice-fish farming provides a competitive and sustainable alternative to intensive rice-farming if the farmer restricts the use of pesticides. This approach not only helps to reduce production costs, but also decreases negative environmental and health impacts (Ahmed and Garnett, 2011; Berg and Tam, 2018).

6.3.1. Pangasius (*Pangasius hypophthalmus*, *P. bocourti*) are facultative air-breathers, which means that they can withstand dissolved oxygen at levels as low as 0.05–0.10 mg/l, high turbidity and highly polluted water, due to an ability to spend the majority of their time near the surface (<1m) where DO is closer to the recommended range of 2.5–7.5 mg/l) (Waycott, 2015).

To maintain water quality and fish health in densely stocked ponds, the water is chemically as well as biologically treated using a large array of chemicals, including antibiotics, biocides, vitamins and digestive drugs (Nguyen *et al.*, 2015). Pond water in high density systems is exchanged on a frequent basis (from weekly to twice a day depending on fish age) to prevent toxic substances such as ammonia, nitrite, hydrogen sulphide or pathogens from accumulating as a result of wasted feed and fish excreta. Ponds also release considerable volumes of sludge when the pond sediment is excavated. Related management options are central for an environmental impact assessment (Figure 6.1).

Figure 6.1. Environmental impact analysis for Pangasius farming



Source: Nguyen, C.V. 2017. An overview of agricultural pollution in Vietnam: The aquaculture sector. Prepared for the World Bank, Washington, DC; after Anh, P.T., Kroeze, C., Bush, S.R. & Mol, A.P.J. 2010a. Water pollution by pangasius production in the Mekong Delta, Vietnam: Causes and options for control. Aquaculture Research, 42: 108–128.

As pond water constitutes a point source of pollution, it should be collected and treated according to national regulation standards before being discharged into open water bodies. However, this requirement is seldom enforced, especially as land suitable for fish farming can be very expensive, and farmers try to minimize the area devoted to waste treatment systems such as sedimentation or wastewater treatment ponds.

Anh *et al*. (2010a) suggest two approaches for ameliorating the impacts of water pollution, contaminated sediment and disease spread: (i) waste prevention and minimization at source, and (ii) treatment and/or onsite or offsite recycling and re-use of waste materials in other production processes (Table 6.7).

Although national regulations have become more rigorous in Viet Nam, market incentives have seemingly proven more effective in motivating farmers. Since 2010, a growing number of intensive Pangasius farms in Viet Nam have improved their wastewater and other management practices to gain access to export markets that require certification under standards, such as those established by **GLOBAL**G.A.P and the Aquaculture Stewardship Council (ASC). In this context, private agribusiness companies have become increasingly proactive in working with farmers, collectors, wholesalers and processors in the value chain to control efficiency at every step of production. Under contract farming arrangements, farmers are typically required to follow the guidance/instructions of agribusinesses, especially on the use of inputs, leading to improvements in both product and environmental health (Nguyen, 2017). The need for such controls and certificates became clear with reports in European media that imported Pangasius is highly toxic. However, toxicological risk assessment failed to find related evidence of pesticides and antibiotics in sufficient amounts to pose a risk (Murk *et al*., 2018).

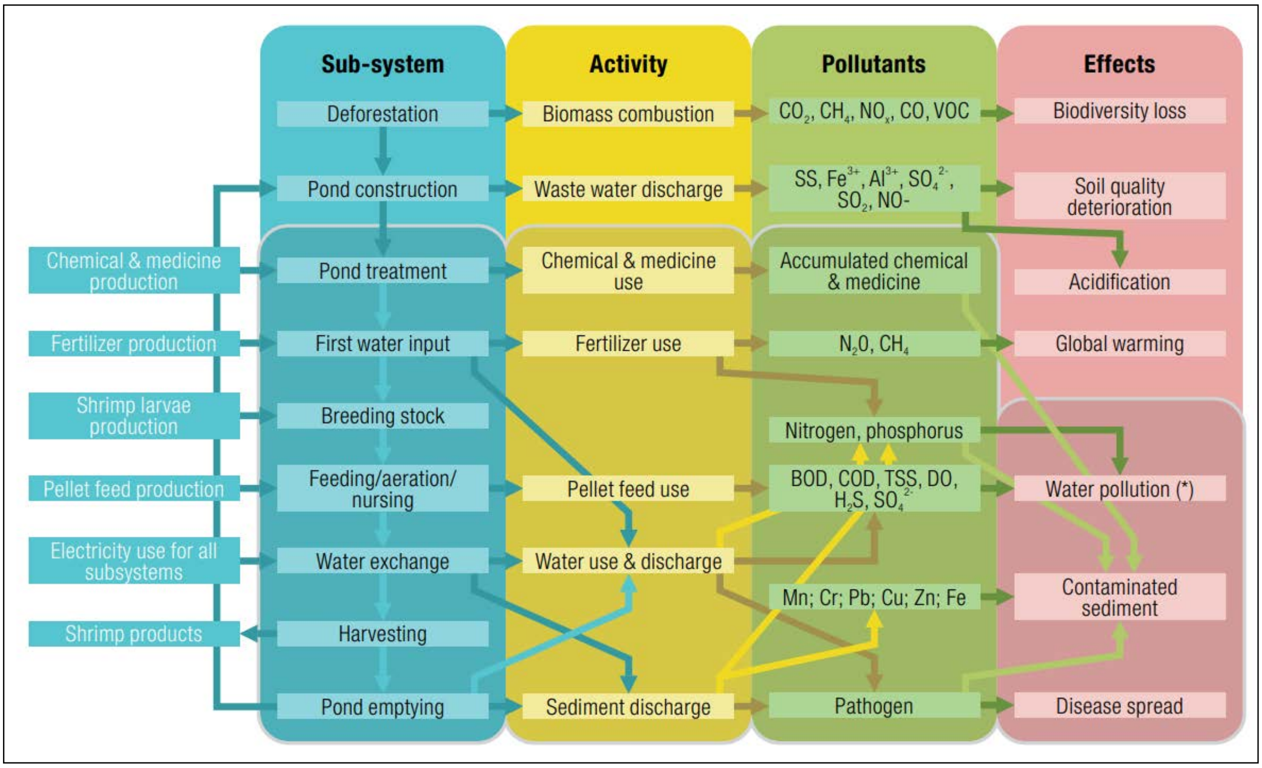
Table 6.7. Options for the reduction of water pollution by Pangasius farming in the Mekong Delta

Name of option	Description of the option	Pollutants or problems reduced	Subsystem and activity to be applied	Remarks	Currently applied/ Costs
Waste prevention and minimization at source					
Water use reduction	Techniques for cleaning water so that less pumping is needed: ozone aeration and probiotic use	Volume of wastewater	Water refreshment	Reduce volume of water use and wastewater	Hardly applied:
Feed use reduction	More efficient feed use: replace homemade feed by good quality pellet feed	BOD, COD, SS	Feeding	Reduce surplus feed sediment	At least half of the farms use homemade feed; pellet feed more expensive
Chemical, medicine use reduction	Techniques for efficient use of chemicals and drugs	Accumulated chemicals and drugs; anti-microbial resistance	Pond treatment/ nursing	Reduce amount of accumulated chemicals and drugs in the sludge	Not applied; if applied appropriately, positive benefit-cost ratio
Treatment of inlet water and good farm cleaning	Techniques for cleaning farms and filtering inlet water	Risk of pangasius disease and dead fish	First water input, Water intake and pond emptying	Reduce risk of disease and dead fish, (one of the cause of water pollution)	Filtering is not applied; relatively costly
Treatment and reuse of water stream					
Sludge treatment in sedimentation ponds	Using a pond for settling the sludge, the effluent can be treated as wastewater	All substances	Frequency sludge discharge and pond emptying	Dewatering sludge can be used for leveling of low land or putting in fruit garden	<10% of farms applied; costs are relatively low if land is available
Treatment of wastewater in constructed wetlands	Sub-surface horizontal flow constructed wetland is possible	All substances	Water exchange pond emptying and effluent from sediment pond	Land scarcity is a challenge	Not applied; costs are moderate if land is available
Reuse wastewater with optimization of the discharge design	Land treatment of wastewater in agriculture	All substances	Water exchange and pond emptying	Investment costs can be considerable, the additional operational costs are relatively low.	Pilot for use of wastewater in rice field, no optimization of discharge design yet

Source: Anh, P.T., Kroeze, C., Bush, S.R. & Mol, A.P.J. 2010a. Water pollution by pangasius production in the Mekong Delta, Vietnam: Causes and options for control. Aquaculture Research, 42: 108–128.

6.3.2. Shrimp farming. The effects of shrimp farming on the environment vary in relation to the shrimp varieties and different farming practices used in their cultivation. Black tiger shrimp, for example, are raised in Viet Nam in either intensive or extensive systems, while white-leg shrimp are exclusively raised in intensive systems. A larger proportion of intensive operations are characterized by higher stocking density and the use of pelleted feed, whereas a lower share of extensive systems involve little, if any, feeding to supplement what is naturally available. White-leg shrimp farms make intensive use of feeds, pond chemicals (pesticides, etc.) and drugs (in particular different antibiotics) against diseases. During harvest, most intensive farms discharge pond water to wastewater treatment systems, whereas most semi-intensive farms drain pond water to the water bodies without proper treatment. In terms of solid waste, the rate of sediment accumulation in intensive shrimp ponds depends on stocking density and the type of commercial pelleted feeds that are used. Pond muds/sludge are flushed to storage sites where they may receive treatment, but in other cases are discharged to canals or rivers, which are important variations for an environmental impact assessment (Figure 6.2).

Figure 6.2. Environmental impact analysis for shrimp farming



Source: Nguyen, C.V. 2017. An overview of agricultural pollution in Vietnam: The aquaculture sector. Prepared for the World Bank, Washington, DC; after Anh, P.T., Kroeze, C., Bush, S.R. & Mol, A.P.J. 2010b. Water pollution by intensive brackish shrimp farming in South-East Vietnam: Causes and options for control. Agricultural Water Management, 97: 872–882.

Intensive shrimp production in Viet Nam has been estimated to generate about 4.4 billion m^3 of wastewater in 2014, including 25 344 tonnes of N (19 800 tonnes from wastewater and 5 544 tonnes from sludge) and 6 336 tonnes of P (2 442 tonnes from wastewater and 3 894 tonnes from sludge). It is estimated that approximately 75 percent of this wastewater was discharged to local rivers in coastal areas of the Mekong Delta (Nguyen, 2017).

A 2015 study estimated that intensive shrimp farms in Vietnam were devoting 17 percent of their farmland, on average, to treatment ponds. Techniques include the use of algae, bacteria and tilapia to remove organic contents, as well as pond rotations or closed water recirculation systems to avoid incoming diseases. The rate of environmental compliance has increased significantly from less than 10 percent in 2013 to over 50 percent in 2016 (Long & Hien, 2015; Nguyen, 2017).

Similar to Pangasius farming, Anh *et al.* (2010b) suggest two approaches for ameliorating the impacts of water pollution, contaminated sediment and disease spread: (i) waste prevention and minimization at source, and (ii) treatment and reuse of effluent streams (see Table 6.8 and Table 6.9).

Table 6.8. Waste prevention and minimization at source (shrimp farming)

Options	Description	Pollutions/ problems reduced	Sub-System to be applied	Problems reduced			Remarks
				WP	CS	DS	
Water use reduction	Ozone aeration	BOD, COD, pathogens, water use, wastewater generation	Aeration/ water	+++	+++	+++	Need a technical transfer to farmer; could be limited to this last grow out phase
Feed use reduction	More efficient feed use: careful in checking optimum use of feed	BOD, COD, pathogens	Feeding	++	++	++	Information exchange on experiences with different types of feeds needed, and exact information on composition of feed
Chemical, medicine use reduction	Better guidelines and monitoring for correct use of chemical and medicine are needed	Accumulated chemical and medical components in water and sediment	Pond treatment/ nursing	+	+	+	Could reduce build-up of anti-microbial resistance

WP: Water pollution; CS: Contaminated sediment; DS: Disease spread; + indicates a moderate improvement, ++ a considerable improvement, +++ a large improvement.

Source: Anh, P.T., Kroeze, C., Bush, S.R. & Mol, A.P.J. 2010b. Water pollution by intensive brackish shrimp farming in South-East Vietnam: Causes and options for control. Agricultural Water Management, 97: 872–882; modified.

Table 6.9. Treatment and reuse of effluent streams from shrimp farming

Options	Description	Sub-System to be applied	Problems reduced			Remarks
			WP	CS	DS	
Treatment and reuse of sediment	Production of compost or soil conditioner from sediment. Application of probiotics to pond sediments could accelerate decomposition	Sludge discharge	+	+++	+	Local research required, e.g., to optimize retention time vs. land requirements.
Treatment and reuse of wastewater	Use mangrove forest wetlands or constructed wetlands	Wastewater discharge	++	+	+	For mangroves to remove nutrients about 2–3 ha are needed per hectare of semi-intensive shrimp ponds.
Wastewater and sediment discharge	Optimization of farm design to ensure that wastewater does not return directly to the surface water.	Water and sediment discharge	+	+	++	

WP: Water pollution; CS: Contaminated sediment; DS: Disease spread; + indicates a moderate improvement, ++ a considerable improvement, +++ a large improvement.

Source: Anh, P.T., Kroeze, C., Bush, S.R. & Mol, A.P.J. 2010b. Water pollution by intensive brackish shrimp farming in South-East Vietnam: Causes and options for control. Agricultural Water Management, 97: 872–882; modified.

Based on the scale and potential of intensive shrimp farming in Vietnam the most viable options for waste reduction include more efficient feed use and ozone aeration. For the reduction of feed it is important that adequate and sufficient information is available to farmers and that the government can efficiently regulate the quality and composition of feeds. Aeration is noted as a particularly suitable technology given the low level of expense needed to implement it in existing intensive systems. Options for waste treatment through sediment reuse and the construction of artificial wetlands are both viable options if the economics can be justified to farmers. Wetland construction, although practiced on some farms, remains difficult to implement due to the lack of land available to farmers, especially in peri-urban areas (Anh *et al.*, 2010b).

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Chapter 7

Livestock and water quality

Camillo De Camillis, Pay Drechsel and Eran Raizman

Global population growth has provoked an increase in global water demand across all sectors, and the livestock sector is no exception. Agriculture accounts for approximately 70 percent of available freshwater supply of which global livestock production represents about 30 percent. This proportion includes rain and irrigation water used for the production of feed and withdrawals for livestock husbandry (Mekonnen & Hoekstra, 2012), with a large proportion allocated to beef production. The relationship between water quality and livestock is double-edged: livestock require quality water, but the waste they produce can deteriorate water quality.

Nitrogen (N) is one of the key parameters for livestock drinking water quality, however livestock is also responsible for major nitrogen releases into nature. One-third of human-induced reactive nitrogen losses can be traced to livestock systems. Most nitrogen is emitted in two forms: Nitrate (NO_3^-, 45 percent), which degrades water quality in freshwater and coastal systems, and ammonia (NH_3, 41 percent), which contributes to air pollution and causes eutrophication and acidification (Mueller & Lassaletta, 2020). N emissions are also precursor to the formation of fine particles which enter the respiratory tract affecting public health (Cohen *et al.*, 2017).

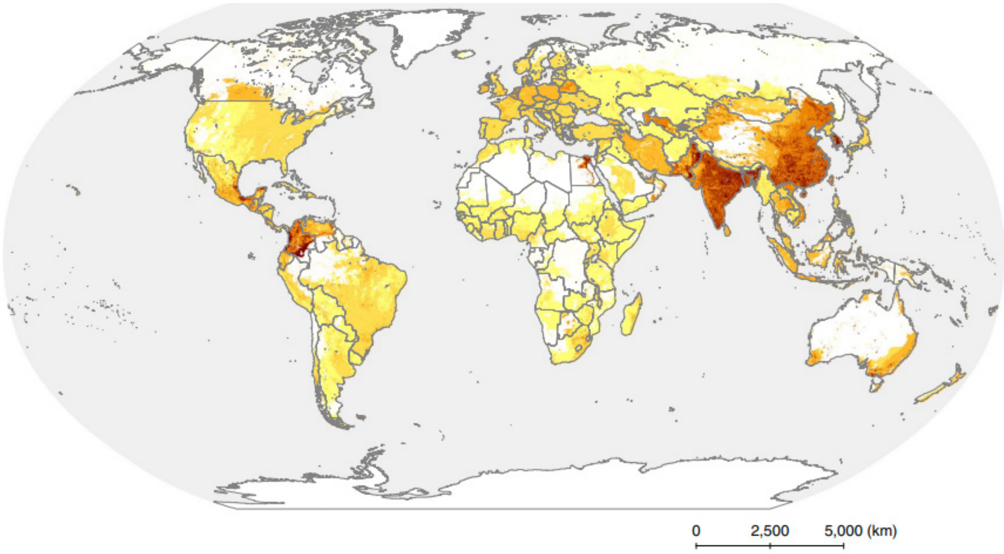
Figures 7.1 and 7.2 show the global distribution of nitrogen emissions from livestock supply chains taking into consideration the diversity of livestock species, systems, production intensity, and the origins and management of different animal feed (Uwizeye *et al.*, 2020).

The Livestock Environmental Assessment and Performance Partnership (FAO LEAP), a multi-stakeholder initiative designed to build consensus on how to assess the environmental impacts of livestock systems, has developed several FAO guidance documents that consider, among others, the water footprint of livestock based on the life cycle assessment methodology and data collection in accordance with ISO 14046:2014[1]. The water footprint of large ruminants consists primarily (often by over 90 percent) of the water needed for (irrigated) feed production, in addition to the direct water footprint associated with drinking water and the consumption of service water (Chapagain & Hoekstra, 2003). The guidelines suggest discussion of the impact of livestock supply chains on water consumption and water quality in defined system boundaries (FAO, 2015).

While livestock water use is associated with livestock watering, feedlots, dairy operations, servicing (including farm and slaughterhouse cleaning), and other on-farm needs, this chapter focuses (i) on the water needs and quality that impact animal health and production, and (ii) the possible burden of livestock waste on water resources.

[1] ISO 14046:2014 specifies principles, requirements and guidelines related to water footprint assessment of products, processes and organizations based on life cycle assessment (LCA).

Figure 7.1. Global distribution of nitrate (NO_3) emissions from livestock supply chains



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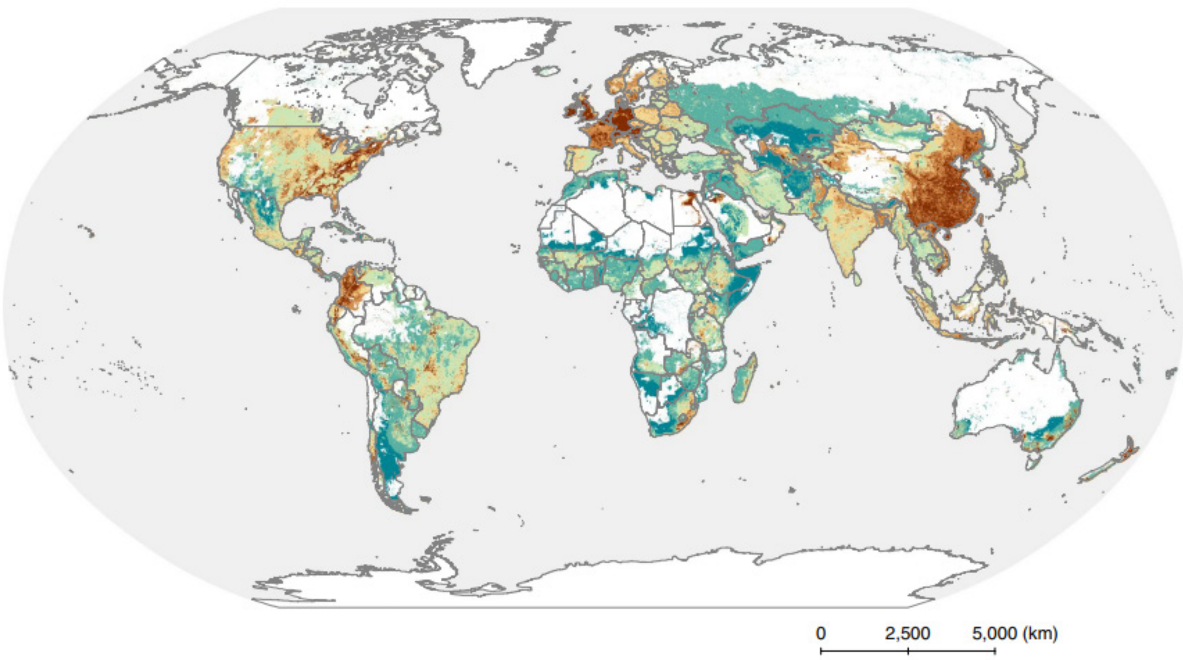
Notes: Final boundary between the Sudan and South Sudan has not yet been determined. Final status of the Abyei area is not yet determined. Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.

Figure 7.2. Global distribution of ammonia (NH_3) emissions from livestock supply chains



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7.1. Water quality specifications for selected parameters potentially affecting livestock health

The water requirements of livestock depend on physiological and environmental conditions. Consumption may vary greatly depending on the species, size and age of the animal, the physical state, the level of activity, food intake, the quality and temperature of water, and the environmental temperature. Because water plays a critical role in animal health, it is essential to provide clean and sufficient water for livestock.

The vast majority of actual water required by animals is obtained as drinking water, followed by the water content of the feed. It is estimated that livestock bodies contain between 60 percent and 70 percent water, which is necessary for maintaining body fluids and proper ion balance; as well as functions such as digestion, absorption and metabolizing nutrients; the elimination of waste material and excess heat from the body; the provision of a fluid environment for foetuses; and transporting nutrients to and from body tissues. Several parameters should be considered when assessing water quality for livestock. These are:

- sensory (organoleptic) attributes such as odour and taste;
- physiochemical properties (pH, salts/total dissolved solids, hardness);
- chemical composition
    - toxic compounds (heavy metals, pesticides, herbicides, etc.);
    - excess minerals or compounds such as nitrates;
    - biological contaminants (bacteria, algae, etc.);
    - spills of petroleum, etc.

Water quality monitoring and evaluation is an ongoing process that requires regular access to a laboratory. The adverse effects of water on animal health and production depend on the location and might be related to high concentrations of minerals (e.g. nitrates and nitrites, sulfate salts, Mg), high levels of pathogenic bacteria causing infections, heavy growth of blue-green algae, and water contamination with chemical substances associated with agriculture and industrial activity such as pesticides and herbicides. Some of the thresholds for water quality parameters are presented below.

7.1.1. Salinity-related toxicity

Excessively saline water may cause salt poisoning in livestock or stop animals from drinking, leading to a loss of production. Tolerance levels of salts[2] [3] [4] are commonly measured in terms of total dissolved solids (TDS), which have been assessed for a number of livestock/animal species (Table 7.1).

[2] https://www.agric.wa.gov.au/livestock-biosecurity/water-quality-livestock?page=0%2C0#smartpaging_toc_p0_s5_h2
[3] https://www.msdvetmanual.com/toxicology/salt-toxicosis/salt-toxicosis-in-animals
[4] https://extension.missouri.edu/eq381#mineralized

Table 7.1. Approximate tolerances of livestock to dissolved salts (salinity) in drinking water (TDS in mg/L)

Livestock	A: No adverse effects on animals expected (mg/L)	B: Animals may initially exhibit reluctance to drink or there may be some scouring, but stock should adapt without loss of production (mg/L)	C: Loss of production and decline in animal condition and health would be expected. Livestock may tolerate these levels for short periods if introduced gradually (mg/L)
Beef cattle (mature, on dry pasture)	0–4 000	4 000–5 000	5 000–10 000
Beef cattle (feedlots)	0–4 000		>4 000b
Dairy cattle (mature, dry)	0–2 400	2 400–4 000	4 000–7 000
Dairy cattle (milking)			3 500
Sheep (mature, on dry pasture)	0–4 000	4 000–10 000	10 000–13 000a
Sheep (mature, dry, feedlots)	0–4 000		>7 000b
Sheep (mature, dry confinement feeding)	0–4 000		>7 000c
Sheep (weaners, lactating and pregnant on pasture)	0–4 000		6 600
Sheep (lambs, intensive feeding)	0–4 000		>4 000b
Horses	0–4 000	4 000–6 000	6 000–7 000
Poultry	0–2 000	2 000–3 000	3 000–4 000
Pigs	0–4 000	4 000–6 000	6 000–8 000

[a] Sheep on lush green feed may tolerate up to 13 000 mg/L TDS without loss of condition or production.

[b] Intensive feeding for growth.

[c] Confinement feeding for maintenance.

Source: DPIRD https://www.agric.wa.gov.au/livestock-biosecurity/water-quality-livestock

Salinity caused by the presence of salts is strongly correlated with electrical conductivity (EC) of the water. It is therefore more common and practical to measure conductivity rather than TDS, and subsequently convert the EC value to TDS[5]. The EC units used are milliSiemens per metre (mS/m). Table 7.2 summarizes the guidance values of EC thresholds applicable to livestock.

[5] See www.agric.wa.gov.au/livestock-biosecurity/water-quality-livestock.

Table 7.2. Electrical conductivity specifications for livestock and poultry.

Water salinity (EC) (dS/m)	Rating	Remarks
<1.5	Excellent	Usable for all classes of livestock and poultry.
1.5–5.0	Very satisfactory	Usable for all classes of livestock and poultry. May cause temporary diarrhoea in livestock not accustomed to such water; watery droppings in poultry.
5.0–8.0	Satisfactory for livestock	May cause temporary diarrhoea or be refused at first by animals not accustomed to such water.
	Unfit for poultry	Often causes watery faeces, increased mortality and decreased growth, especially in turkeys.
8.0–11.0	Limited use for livestock	Usable with reasonable safety for dairy and beef cattle, sheep, swine and horses. Avoid use for pregnant or lactating animals.
	Unfit for poultry	Not acceptable for poultry.
11.0 – 16.0	Very Limited Use	Unfit for poultry and probably unfit for swine. Considerable risk in using for pregnant or lactating cows, horses or sheep, or for the young of these species. In general, use should be avoided, although older ruminants, horses, poultry and swine may subsist on waters such as these under certain conditions.
>16.0	Not Recommended	Risks with such highly saline water are so great that it cannot be recommended for use under any conditions.

Source: Ayers, R.S. & Westcot, D.W. 1994. Water quality for agriculture. FAO Irrigation and Drainage Paper 29, Rev. 1. Rome

Among salinity-causing salts, those containing sulphate can be particularly relevant for livestock, especially in location where the hot climate evaporates surface waters, increasing salt concentrations. Table 7.3 gives related guidelines (German, Thiex & Wright, 2008) in this regard. In general, the maximum concentration of sulphate (SO_4) in drinking water for livestock, which is often set as 1 000 mg/l, depends significantly on the additional sulphate intake through feed (i.e. the dietary sources). Water consumption by cattle begins to decrease at sulphate (SO_4) levels of 2 500 to 3 000 mg/L, which will lead eventually to dehydration and death[6].

[6] https://waterquality.montana.edu/well-ed/interpreting_results/fs_livestock_suitability.html and https://agriculture.canada.ca/en/agriculture-and-environment/agriculture-and-water/livestock-watering/water-quality-impacts-livestock

Table 7.3. A guide to the use of water containing sulfates for livestock and poultry

Sulfate (SO_4) mg/L or ppm	Comments
Less than 250 (poultry)	Recommendations for poultry are variable. The more conservative guidelines indicate that sulfate content above 50 mg/L may affect performance if magnesium and chloride levels are high. Higher sulfate levels have a laxative effect.
Less than 1500 (livestock)	For livestock, no harmful effects- except some temporary, mild diarrhea near upper limit, and animals may discriminate against the water due to taste at the upper limit. The calculations of total sulfur intake is recommended when using sulfur-containing feeds (e.g., molasses, distiller's grains, corn gluten feed).
1500-2500	For livestock, no harmful effects- except some temporary diarrhea. In cattle this water may contribute significantly to the total dietary sulfur intake. May cause a reduction in copper availability in ruminants. Calculating total sulfur intake is recommended.
2500-3500	Poor water for poultry, especially turkeys. Very laxative, causing diarrhea in livestock that usually disappears after few weeks. Sporadic cases of sulfur- associated polioncephalomalacia (PEM) are possible. May cause substantial reduction in copper availability in ruminants. The calculation of total sulfur intake is recommended.
3500-4500	Very laxative. Unacceptable for poultry. Not recommended for use for pregnant or lactating ruminants or horses, or for ruminants fed in confinement. Sporadic cases of sulfur-associated polioncephalomalacia (PEM) are likely. May cause substantial reduction in copper availability in ruminants. The calculation of total sulfur intake is recommended.
Over 4500	Not recommended for use under any conditions. The calculation of total sulfur intake is highly recommended. Increased risk of mortality and morbidity.

Source: German, D., Thiex, N. & Wright, C. 2008. Interpretation of water analysis for livestock suitability. Brookings, SD, South Dakota State University, South Dakota counties, and U.S. Department of Agriculture

Sulphate containing salts are often sodium (Na_2SO_4) or magnesium ($MgSO_4$) based. In general, sodium concentrations under 1 000 mg/l should be protective for livestock, unless sulphate levels are also high (Table 7.4). Sodium values above 5 000 mg/l can cause serious effects and death. Short-term exposure should not exceed 4 000 (MSU, 2021).

Table 7.4. A guide to the use of water containing sodium for livestock and poultry

Sodium (Na) mg/L or ppm	Comments
Less than 50 (poultry)	Sodium levels pose little risk to poultry.
50 – 1000 (poultry)	Recommendations are extremely variable and sodium itself poses little risk; however, water with sodium over 50 mg/L (ppm) may affect the performance of poultry if the sulfate or chloride is high. Sodium levels greater than 50 mg/L are detrimental to broiler performance if the sulfate level is also 50 mg/L or higher and the chloride level is 14 mg/L or higher. Excessive sodium has a diuretic effect for poultry.
Less than 800 (livestock)	By itself, sodium poses little risk to livestock, but its association with sulfate is a concern. Water with over 800 mg sodium /L can cause diarrhea and a drop in milk production in dairy cows. High levels of sodium, a major component of salt, may necessitate adjustments to rations. Care should be taken when removing or reducing salt from swine and diary rations to ensure a chlorine deficiency does not result. Salt may be reduced in swine diets if the sodium in the water exceeds 400 mg/L.

Source: German, D., Thiex, N. & Wright, C. 2008. Interpretation of water analysis for livestock suitability. Brookings, SD, South Dakota State University, South Dakota counties, and U.S. Department of Agriculture

Magnesium-based salts in cattle trigger a stronger sulfate response than sodium-based salts for which many animals have developed a recognized appetite (Grout *et al.*, 2006). Table 7.5 shows the related drinking water guidelines for magnesium.

Table 7.5. Specifications for magnesium in drinking water for livestock

Livestock	Magnesium (mg/l)
Horses	250
Beef cattle	400
Cows (lactating)	250
Adult sheep on dry feed	500
Ewes with lambs	250

Source: Ayers, R.S. & Westcot, D.W. 1994. Water quality for agriculture. FAO Irrigation and Drainage Paper 29, Rev. 1. Rome

7.1.2. Trace elements

Trace elements can be important for livestock growth, but become a problem if they exceed certain thresholds. In particular, metals in drinking water can lead to toxic outcomes in animals. Some metals are geogenic in origin (i.e. inherited with location), while others are introduced due to anthropogenic activities. As trace metals can accumulate slowly, monitoring should therefore be performed periodically. Table 7.6 gives the upper limits for selected contaminants.

Table 7.6. Specifications for limit values for trace metals in drinking water for livestock

Constituent (symbol)	Upper limit (mg/l)
Aluminium (Al)	5
Arsenic (As)	0.2
Beryllium (Be)[1]	0.1
Boron (B)	5
Cadmium (Cd)	0.05
Chromium (Cr)	1
Cobalt (Co)	1
Copper (Cu)	0.5
Fluoride (F)	2
Iron (Fe)	No reported toxicity
Lead (Pb)[2]	0.05-0.1
Manganese (Mn)[3]	0.05
Mercury (Hg)	0.01
Nitrate + Nitrite (NO_3-N + NO_2-N)	100[4]
Nitrite (NO_2-N)	10
Selenium (Se)	0.05-0.1
Vanadium (V)	0.1
Zinc (Zn)	24

[1] Insufficient data for livestock. The value for marine aquatic life is used here.
[2] Lead is accumulative and problems may begin at a threshold value of 0.05 mg/l.
[3] Insufficient data for livestock. The value for human drinking water is used here.
[4] These levels are rarely seen in surface water except in extremely contaminated water bodies, but can be found in groundwater.

Source: Ayers, R.S. & Westcot, D.W. 1994. Water quality for agriculture. FAO Irrigation and Drainage Paper 29, Rev. 1. Rome

Nitrate is a particular common contaminant strongly influenced by human activities. Nitrate intake occurs mainly through feed and drinking water. Elevated levels may be found in forage due to heavy use of nitrogen fertilizer in fields or other types of water pollution. While acute nitrate poisoning is rare, elevated levels of nitrates in water for livestock or poultry may result in possible effects, which are presented in Table 7.7.

Table 7.7. Possible effects of nitrates in water for livestock or poultry (in mg/L or ppm)

Nitrate level as NO_3 [a]	Nitrate level as NO_3-N [a]	Possible effects [b]
0 to 100	0 to 23	Unlikely for livestock or poultry
101 to 500	23 to 114	Possibility of reduced gains, increased infertility
501 to 1 000	115 to 227	The water should not harm livestock or poultry by itself, but in combination with normal nitrate intake through feed can result in distress symptoms (shortness of breath, rapid breathing)
over 1 000	over 227	Suffocation signs, lack of coordination or staggering, ultimately death of cattle, sheep or horses

[a] When a laboratory reports the concentration of nitrate, it might refer to the nitrate ion (NO_3-) or to the nitrogen within the nitrate ion (NO_3-N).
[b] Assumes normal or close to average nitrate levels in forage and feed.

Sources: Adams, R.S., McCarty, T.R. & Hutchinson, L.J. 2021. Prevention and control of nitrate toxicity in cattle. University Park, PN, Pennsylvania State University; German, D., Thiex, N. & Wright, C. 2008. Interpretation of water analysis for livestock suitability. Brookings, SD, South Dakota State University, South Dakota counties, and U.S. Department of Agriculture

7.1.3. Pesticides, herbicides and pharmaceutics

The Canadian Environmental Quality Guidelines online database contains a large range of pesticides, herbicides, other organic contaminants and heavy metals that may be found in livestock drinking water (CCME, 2021). A comparison of the different regulations governing these substances is found in Valente-Campos *et al.* (2014). Although drinking water can contain pharmaceutical residues, related guidelines for livestock have emerged only slowly as concentrations remained very low for many years compared, for example, with those of purposely administered antibiotics (e.g. through feed or water). The use of antibiotics for growth promotion purposes was banned in the European Union in 2006, and the use of sub-therapeutic doses of medically important antibiotics in animal feed and water became illegal in the United States on 1 January 2017. More bans are expected as awareness increases of the risk of transmitting drug-resistant bacteria to humans, accompanied by calls for standards for total livestock and poultry intake (including via water).

7.1.4. Water-borne microbial infections

Several microbes, some of them zoonotic in nature, have been associated with water transmission and disease outbreaks. The risk of contamination is greatest in surface waters (dams, lakes, dugouts, etc.) that are directly accessible by stock, or that receive runoff or drainage from intensive livestock operations or human waste. In comparison, groundwater is considered a low-risk source (Olkowski, 2009).

Bacterial pathogens: The pathogens of greatest concern in water supplies for farm animals include enteric bacteria such as *E. coli*, *Salmonella*, *Clostridium botulinum* and *Campylobacter jejuni*. The presence and survival of bacteria in natural aquatic ecosystems depends upon a number of factors, including nutrient content, exposure to direct sunlight and temperature, and competition with other microorganisms. Strict tolerance values for livestock have not been established. It is however often recommended that drinking water for livestock should contain less than 100 coliforms/100 ml.

Botulism and salmonellosis are two bacterial livestock diseases that may result from contamination of water with organic matter:

- Botulism is a rapid-onset, usually fatal disease caused by the botulinum toxin produced by the bacterium *Clostridium botulinum*. Typical signs include hindlimb weakness progressing to paralysis, collapse and death. Common sources of the toxin include animal carcasses, rotting organic material and poorly prepared silage. Treatment is rarely attempted but vaccines are available for disease prevention in cattle. For more information see www.agric.wa.gov.au/livestock-biosecurity/botulism-cattle.
- Salmonellosis of sheep is an infectious bacterial disease causing illness and death. It results from proliferation of salmonella bacteria in the gastrointestinal tract and other organs. A possible source can be faecal contamination of feed or water. Profuse diarrhoea is commonly present and pregnant ewes may abort. For more information see www.agric.wa.gov.au/livestock-biosecurity/salmonellosis-sheep.

Of particular importance are water sources such as reservoirs used by cattle and humans. Cattle are considered a primary source of *E. coli* O157, which is one of the Shiga toxin-producing *E. coli* (STEC) strains. These toxins usually do not cause disease in animals but may cause watery diarrhoea. Water contaminated with cattle faeces, as well as direct or indirect contact with live cattle, are considered major routes of human infection. Cattle that carry *E. coli* O157 can thus be asymptomatic, but in humans this pathogen creates severe zoonotic infections, and in many cases is the cause of death (Olkowski, 2009).

Protozoan: *Cryptosporidium spp*. are protozoan parasites that affect livestock, some of which are of public health importance due to their ability to cross over to humans. Transmission occurs via water, therefore, water sources in production systems should be monitored carefully. Among the many species which can infect human, cattle, small ruminants and poultry, *C. parvum* and e.g. *C. andersoni* are some of the most prevalent, affecting young livestock, especially pre-weaned ruminants (Fayer, 2004).

Algae: Livestock can be poisoned by drinking water contaminated with blue-green algae (*Cyanobacteira*) and associated natural toxins such as acute hepatotoxins, cytotoxins, neurotoxins and toxins causing gastrointestinal disturbance. Blue-green algae are a group of bacteria that include *Nodularia spumigena*, *Microcystis aeruginosa* and *Anabaena circinalis*. They can produce spectacular blooms which resemble iridescent green paint or curdled greenish milk on water surfaces. Algae multiply rapidly ("bloom") in shallow, stagnant and warm water when the water is contaminated by plant nutrients, including organic and faecal matter and phosphorus. Identification of cyanobacteria and especially the *Microcystis* species (Table 7.8) is difficult. The various species can be identified by experts with a microscope, but in the field such determination is limited to whether the bloom is filamentous (stringy) or planktonic. Filamentous algae are easily removed from water by hand, whereas planktonic algae/cyanobacteria are single celled and will slip through fingers. No toxin-producing cyanobacteria is of the filamentous type.

Table 7.8. Guideline for calculated tolerance levels (No Observed Effect Level) of microcystin LR toxicity equivalents and number of cells of Microcystis aeruginosa.

Livestock category	Body weight (kg)	Peak water intake (L/day)	Calculated total toxin level (µg/L)	Equivalent cell number (cells/mL)
Cattle	800	85	4.2	21 000
Sheep	100	11.5	3.9	19 500
Pigs	110	15	16.3	81 500
Chicken	2.8	0.4	3.1	15 500
Horse	600	70	2.3	11 500

Source: Olkowski. 2009. Livestock water quality: a field guide for cattle, horses, poultry, and swine. Ottawa, Agriculture and Agri-Food Canada

7.1.5 Good management practices for water quality to keep livestock healthy

The following recommendations should be considered as part of good practices for farm management:

- Assess water quality and quantity for effective production planning. If water quality is poor, livestock may drink less than they need or may stop drinking altogether. When animals drink less, they will eat less resulting in deterioration of their physiological condition. If they are lactating, milk production will reduce or cease.
- Learn from colleagues, veterinarians and water experts about water contaminants that are likely to negatively affect animal health in your area. Seek laboratory support to identify the key parameters of principal water sources (e.g. algae, salinity, pathogens, trace metals, chemicals organic materials, etc.) to determine which ones are likely to play a critical role. This assessment may have to be performed in both the rainy and dry seasons. In the rainy season, more pollutants will be washed into water bodies; in the dry season, salt concentration will increase due to evaporation and less dilution. Where water is scarce and expensive, storage pond cover sheets could be help reduce costs (Martínez Alvarez *et al.*, 2009).
- Develop a Risk Mitigation Plan to monitor critical water parameters on a regular basis and identify changes in water quality before they have an impact on animals. Monitoring livestock health is a particularly important component of risk mitigation due to potential difficulties in analysing possible contaminants. Establishing a working relationship with a veterinarian is essential to ensure that animal health and welfare and disease notification issues are addressed.
- Seek veterinary assistance to immediately investigate any signs of serious disease. The presence of water contaminants in livestock should be identified as early as possible, before the manifestation of adverse health effects in animals. Both producers and water specialists should be trained to recognize subtle adverse effects on growth rate, feed conversion ratio, reproductive success, milk yield and product quality.

Preventive hygiene measures and good management are currently the most important tools to control cryptosporidiosis as chemical disinfectants have shown mixed success. Ensure that animal manure does not enter the drinking water sources of livestock or of farmers downstream. Where drinking water is polluted consider treatment. Several methods and technologies are available to reduce and even eliminate the amount of different contaminates in water. In selecting a method, consider the cost effectiveness of the identified risk factors. Possible options include the following methods:

- *Activated carbon filters:* This method is based on passing water through a filter containing activated carbon granules. The contaminants attach to the granules and are removed. This method is able to remove mercury, some pesticides and volatile organic compounds, among others. Poor filter maintenance will decrease effectiveness, however, and may result in bacterial growth on the filters, potentially contaminating the water with pathogens. It is therefore important to replace the filters often, which increases operational costs.
- *Chlorination:* This is one of the most common methods applied in water treatment to reduce pathogens in drinking water for livestock as well as humans. The chlorination process is very effective when used in conjunction with a filtration system to remove large particles that can house bacteria. However, the chlorine content of the treated water should be closely monitored to avoid possible harm to animals (Olkowski, 2009).
- *Coagulation:* This method is used in livestock operations to remove fine particles, iron, arsenic, manganese and organics. The removal of particles prior to chlorination makes disinfection much more effective. Coagulation is a standard treatment for surface water prior to chlorination. The chemicals used in the process, such as aluminium sulphate (alum), neutralize the charge on the particles and cause them to coalesce into floc that can be removed by filtration or settling (Olkowski, 2009).
- *Sulfate reduction:* Present treatment technologies to reduce sulfates are costly. They include ion exchange and membranes, such as nanofiltration. Due to the high cost, the best option is usually to find another water source with a lower concentration of sulfates.

Avoid water sources that show elevated levels of cyanobacteria (blue algae). The prevention of cyanobacterial blooms is a more cost effective means of reducing the risk of toxicity than the typical water treatment process. Reducing the growth potential of cyanobacteria by lowering nutrient availability, for example, should be the primary goal when seeking to reduce the risks associated with cyanobacterial blooms (Downing, Watson & McCauley, 2001). Other options for eliminating blooms include the use of storage tank covering sheets for light shading (Craig *et al.*, 2005), or the application of chemical algaecides. There is evidence that copper sulfate added to pond water up to a concentration of 1 ppm (1 mg/l) will successfully kill algae blooms, but will also likely harm other types of aquatic life. The Canadian AAFC-PFRA recommends a lower dosage between 0.06 mg/l and 0.25 mg/l based on the surface area of the water body. Treatment at the beginning of the bloom at a low dosage is more effective than later treatment, as it allows the zooplankton to populate and assist in the control of algae and cyanobacteria. It is important to remember that a sudden release of toxins can occur when cyanobacterial blooms die. Hence, the use of chemical algaecides may not eliminate the risk of toxicity; in fact, the risk of toxin exposure may increase if the algaecide is introduced at the wrong time[7].

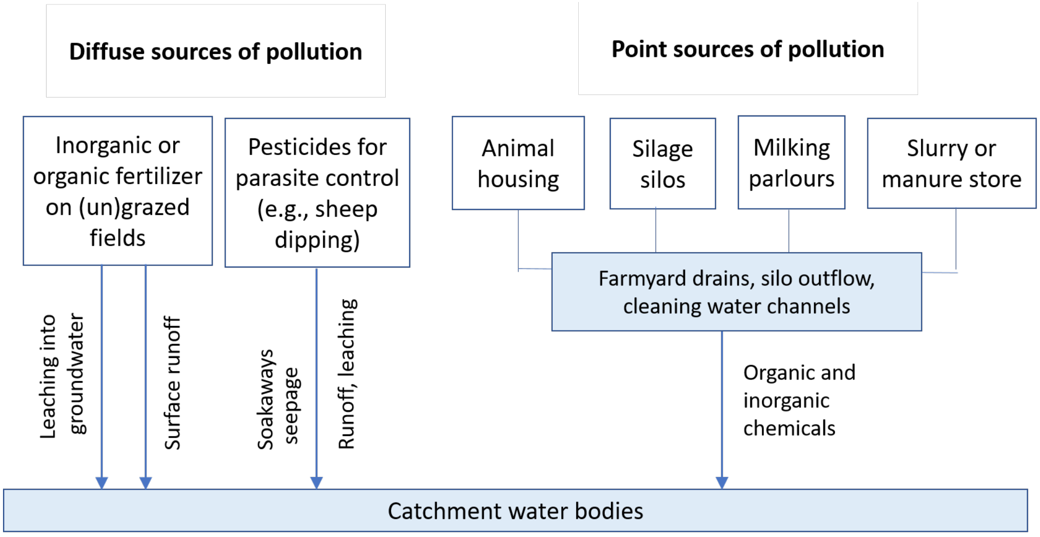
7.2. Livestock impact on water quality

The livestock sector is growing and intensifying faster than crop production in almost all countries, and the associated waste, including manure, has serious implications for water quality. Where livestock is concentrated, the associated production of wastes can surpass the buffering capacity of surrounding ecosystems, thereby polluting surface waters and groundwater (Mateo-Sagasta, Marjani Zadeh & Turral, 2017). Increased loss of nutrients in agricultural runoff has potentially

[7] www.ag.ndsu.edu/waterquality/livestock/Livestock_Water_QualityFINALweb.pdf

serious ecological and public health implications. Nitrogen and phosphorus are of particular significance in this regard, as both can lead to aquatic eutrophication if stemming from diffuse pollution from pasture-based cattle and sheep systems, or point pollution from indoor systems, as it is common for pigs and poultry (Figure 7.3). Finally, feedlots are often located on the banks of watercourses where (nutrient-rich) animal waste (e.g. urine) is released directly into the water.

Figure 7.3. Pathways of diffuse and point sources of nutrients and farm effluent inputs to catchment waters in livestock farming areas



Source: Modified after Hooda, P.S., Edwards, A.C., Anderson, H.A. & Miller, A. 2000. A review of water quality concerns in livestock farming areas. Science of the Total Environment, 250(1–3): 143–167.

The organic and nutrient load of manure (Table 7.9) can consume significant amounts of oxygen in the water body (Table 7.10). Pathogens from livestock waste that are detrimental to public health include bacteria such as *Campylobacter spp.*, *Escherichia coli* O157 (see above), *Salmonella spp.* and *Clostridium botulinum*, and *parasitic protozoa* such as *Giardia lamblia*, *Cryptosporidium parvum* and *Microsporidia spp.*, all of which cause hundreds of thousands of infections every year (Christou, 2011). Figure 7.4 shows the common pathways of microbial water contaminants (Hooda *et al.*, 2000).

Table 7.9. Major nutrients in typical livestock waste

Source	Total nutrients (available fraction in parentheses)		
	N	P	K
	Solids (kg/t)		
Cattle FYM (25% DM)	6 (1.5)	3.1 (0.78)	5.80 (3.48)
Pig FYM (25% DM)	6 (1.5)	2.62 (1.53)	3.31 (2.90)
Broiler litter (60% DM)	29 (10.0)	9.60 (5.67)	13.27 (9.95)
	Slurry (kg/m^3)		
Cattle Slurry (6% DM)	3 (1.0)	0.52 (0.26)	2.98 (2.49)
Pig Slurry (6% DM)	5 (1.8)	1.31 (0.65)	1.99 (1.65)

Note: DM: dry matter; FYM: farmyard manure.

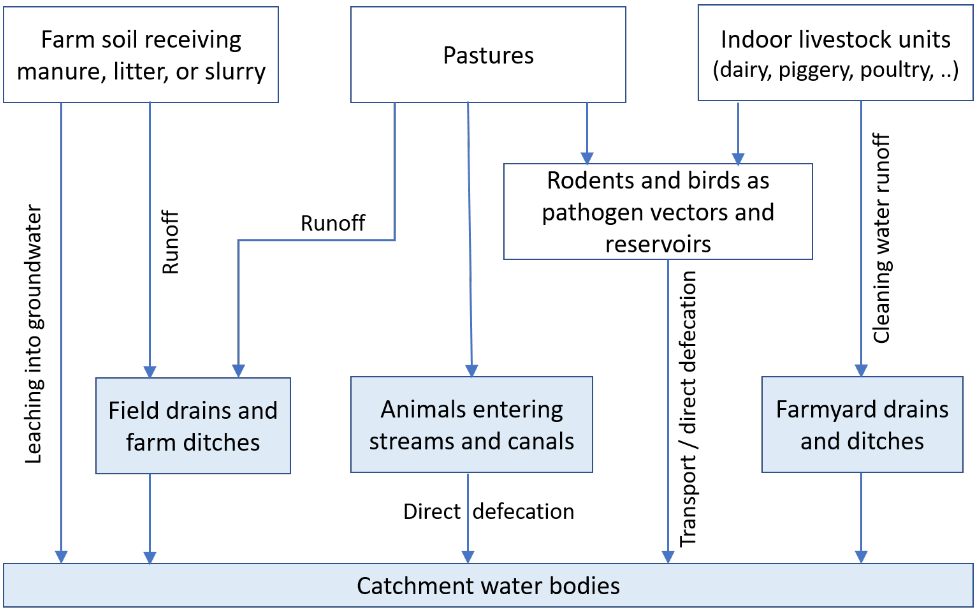
Source: Hooda, P.S., Edwards, A.C., Anderson, H.A. & Miller, A. 2000. A review of water quality concerns in livestock farming areas. Science of the Total Environment, 250(1–3): 143–167, after Webb, J. & Archer, J.R. 1994. Pollution of soils and watercourses by wastes from livestock production systems. In I. Ap Dewi, R.F.E. Axford, I.F.M Marai & H. Omed, eds. Pollution in livestock production systems, pp. 189–204. Wallingford, UK, CAB International

Table 7.10. Ranges of biological oxygen demand (BOD) concentrations for various waste types

Source	BOD (mg/L)
Silage effluents	30 000 - 80 000
Pig slurry	20 000 - 30 000
Cattle slurry	10 000 - 20 000
Liquid effluents draining from slurry stores	1000 - 12 000
Dilute diary parlour and yard washing (dirty water)	1000 - 5000
Milk	140 000
Untreated domestic sewage	300 - 00
Treated domestic sewage	20 – 60
Clean river water	< 5

Source: Hooda, P.S., Edwards, A.C., Anderson, H.A. & Miller, A. 2000. A review of water quality concerns in livestock farming areas. Science of the Total Environment, 250(1–3): 143–167, after Webb, J. & Archer, J.R. 1994. Pollution of soils and watercourses by wastes from livestock production systems. In I. Ap Dewi, R.F.E. Axford, I.F.M Marai & H. Omed, eds. Pollution in livestock production systems, pp. 189–204. Wallingford, UK, CAB International.

Figure 7.4. Pathways of catchment water contamination with microbial and protozoan micro-organisms



Source: Hooda, P.S., Edwards, A.C., Anderson, H.A. & Miller, A. 2000. A review of water quality concerns in livestock farming areas. Science of the Total Environment, 250(1–3): 143–167.

7.2.1. Good management practices to prevent water quality impacts from livestock

Given the high risks involved in compromised water quality, good management practices should be developed to safeguard the health of animals and their environment as well as downstream water sources.

As part of good practices in farm management, it is essential to comply with regulations concerning restrictions on animal movements and stocking rates, and consider the following practices to minimize negative impacts from livestock farming on the environment, in particular the quality of water sources in direct farm proximity:

- Study the landscape and context of the livestock production system to ascertain all the resources needed, in particular the water quality upstream and downstream of the farm or grazing area, the depth of shallow groundwater, the soil texture and infiltration rate. The objective is for the water downstream of the farm to have at least the same quality as the water upstream (i.e. zero negative impact).
- Determine the pollution pathways (see Figure 7.3 and Figure 7.4) of highest probability and the related critical control points for risk monitoring and mitigation.
- Implement measures to reduce farm runoff and leaching (see Chapter 8; ecology), and treat runoff from point pollution sources (e.g. through constructed wetlands) before the waste stream enters off-farm water bodies.

Selected best management practices for livestock safety are described by Hooda *et al.* (2000) and FAO & OIE (2009), among others.

7.3. Conclusion

This chapter describes how poor water quality can affect livestock, and how poor livestock management can affect water quality. It shows how impacts from farming can extend beyond the farm and reasons that such impacts are the responsibility of the farmer. However, as livestock systems differ significantly between animals, it is important to seek advice from extension officers regarding the most appropriate options to safeguard animal and environmental health. While this chapter has focused on low-cost management practices, any option must consider local feasibility and cost-effectiveness. Providing farmers with related guidance is the core task of government authorities and their extension services, local academia and international organizations, who must ensure that access to knowledge, risk awareness, and the capacity to adopt good practices to achieve good water quality management, is available to all types of livestock holders.

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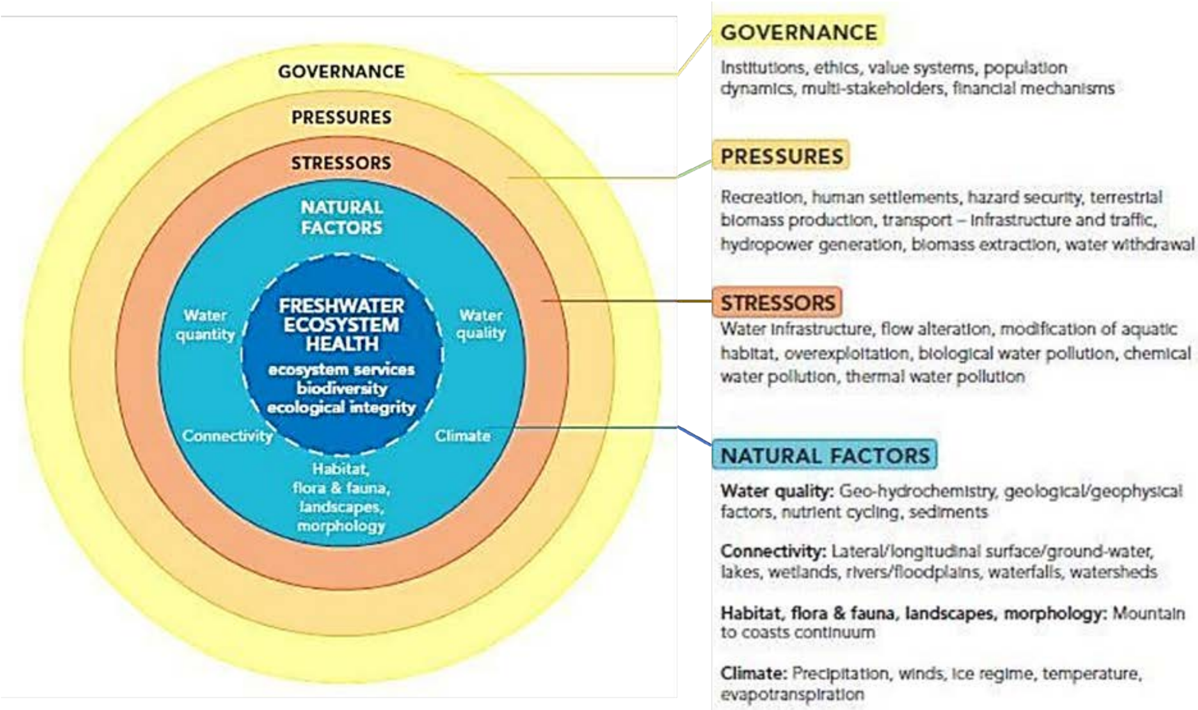
Chapter 8

Ecological risks and risk mitigation measures related to water quality and agriculture

Birguy Lamizana and Pay Drechsel

Freshwater ecosystem health is under multiple pressures (Fig 8.1) with water pollution and quality being a key factor. Farming is in this context an intrusion on the natural habitat and landscape of the environment. The farming of crops (particularly mono-cropping practices) is not only affecting biodiversity but also changes natural water flows and can negatively affect water quality (APO, 2016). While pollution of the natural environment – and water bodies in particular – derives from various point and non-point sources including urban wastewater, this chapter focuses on pollution from agricultural activities, i.e., an aspect over which farmers have control. Possible impacts from pollution related to water quality can be various and relate to both irrigated and non-irrigated (rainfed) cropping, as well as fish and livestock farming.

Figure 8.1. Freshwater ecosystem health under pressure



Source: UNEP. 2018. A framework for freshwater ecosystem management. Volume 4: Scientific background. Nairobi, United Nations Environment Programme.

The most common water pollution pathways in agricultural areas are erosion and water body siltation, farm surface runoff contaminated with fresh manure, fertilizers or pesticides, and saline irrigation drainage water affecting downstream ecology. Nitrogen and phosphorus overuse can also pose a significant threat to environmental health, biodiversity and ecosystem services, especially in locations with high fertilizer application rates.

This chapter briefly describes these risks as well as common indicators and risk mitigation measures of relevance to agriculture. In so doing, it aims to demonstrate the need for a systems or landscape approach when considering downstream impacts through good agricultural practices.

8.1. Risks of relevance to ecology

Rivers, streams and wetlands in general are the receptacle of all kinds of pollution, and constitute pathways for pollutants to coastal and marine waters or lakes. According to UNEP (2016), in Africa, Asia and Latin America, one-third of all rivers are affected by severe pathogen pollution, one-seventh by severe organic pollution, and one-tenth by severe and moderate salinity pollution. Inorganic pollution represents a particular threat to ambient water quality occurring when an excess of easily biodegradable wastes (e.g. nutrients such as phosphorus, nitrogen and potassium from agricultural land, livestock farming or aquaculture) enters rivers and lakes through run-off and erosion (UN Water, 2016). Global estimates suggest that soil erosion by water is responsible for annual fluxes of 23–42 Mt of nitrogen and 14.6–26.4 Mt of phosphorus from agricultural land (FAO & ITPS, 2015).

Nitrates and phosphates can stimulate excessive plant growth and lead to eutrophication – the over-productivity of plant organisms in water – resulting in the creation of algal blooms and the depletion of oxygen concentrations, which in turn decreases aquatic biodiversity (UNEP, 2016; UN Water, 2016). Observed consequences of eutrophication in freshwater wetland systems include shifts in vascular plant species composition due to an increase in above-ground production, a decrease in local or regional biodiversity, growth in the competitive advantage of aggressive/invasive species, loss of nutrient retention capacity (e.g. carbon and nitrogen storage, changes in plant litter decomposition) and shifts in macroinvertebrate composition along an eutrophication gradient (USEPA, 2008). Conservative estimates of the costs of eutrophication amount to USD 1 billion in annual losses for European coastal waters and USD 2.4 billion for lakes and streams in the United States (Wurtsbaugh, Paerl & Dodds, 2019).

Aside agro-chemical transport through run-off and erosion, water quality problems can also arise from suspended soil particles themselves, which cause turbidity and siltation of water bodies, leading eventually to increased sedimentation of reservoirs, for example. While soil erosion and sediment transport are natural processes, deforestation, land clearance for agriculture and inappropriate agriculture practices can substantially increase the amount of suspended solids and turbidity in the water, which can lead to multiple undesirable effects for aquatic plants, algae, invertebrates and fish (Dunlop, McGregor & Horrigan, 2005). Increased turbidity may limit, for example, the growth of bottom-rooted aquatic plants and favour the growth of algae. It can result in reduced visibility for animals that use sight to find food or hide from predators, affect spawning habitats and provoke respiratory problems in fish. Increased sedimentation also leads to infilling of reservoirs, clogging of waterways and alteration of flow patterns (FAO, 2018).

Some 30 percent of the world's freshwater stocks are found beneath ground that is tapped to supply water for domestic and agricultural needs (UNEP, 2010). Depending on the characteristics of farm soils and their underlying geology, groundwater is less exposed to pollutants than surface waters; however, they can be heavily impacted when pollutants infiltrate coarse textured substrates with limited filtration. Contamination of soils and groundwater can be caused by irrigation practices leading to salinity through nitrate and pesticide leaching, or the accumulation of chemicals or pathogens where wastewater is used.

Wetlands can function as natural "kidneys" that filter and improve water quality, attenuate and moderate floodwater flows, replenish groundwater and recharge underlying aquifers. In addition to providing multiple ecosystem services, wetlands also support biodiversity. However, many wetlands have been degraded by excessive volumes of contaminants, or encroachment, diminishing their capacity to improve water quality and provide other services.

8.2. Water quality and ecosystem health criteria

Aquatic life water quality indicators and criteria are essential for the protection of fish and wildlife. In general, indicators for freshwater ecosystems can be categorized in terms of quantity (e.g., flow volumes), quality (e.g., dissolved oxygen, specific nutrients or toxicants), habitat (e.g., substrates, bank stability or riparian vegetation), and biological criteria (e.g., fish, invertebrates, algae) (UNEP, 2018).

Criteria, in particular those showing concentrations of pollutants, are typically expressed in two forms to address unacceptable adverse effects from both short-term (acute) and long-term (chronic) exposure, with the objective of protecting aquatic life from lethal as well as sub-lethal effects, like immobility, slower growth, or reduced reproduction.

Acute and chronic criteria for aquatic life addressing magnitude, duration, and frequency are expressed with two terms (USEPA, 2021):

- Criterion Maximum Concentration (CMC). An estimate of the highest concentration of a material in ambient water to which an aquatic community can be exposed briefly without resulting in an unacceptable adverse effect. This is the acute criterion.
- Criterion Continuous Concentration (CCC). An estimate of the highest concentration of a material in ambient water to which an aquatic community can be exposed indefinitely without resulting in an unacceptable adverse effect. This is the chronic criterion.

The USEPA (2022) national aquatic life criteria recommendations represent specific CMC and CCC levels of inorganic and organic chemicals or conditions in a fresh and salt water body not expected to cause adverse effects to aquatic life.

An alternative framework has been presented by UNEP (2018) based on various national and international guidelines. In Table 8.1 values for physical and chemical indicators of freshwater ecosystem quality are proposed which are indicative of (i) high ecosystem integrity, and (ii) extreme impairment, respectively. The first benchmark value will separate freshwater ecosystems of high integrity (Category 1) from ecosystems in worse quality status. The second benchmark demarcates the low end of the quality continuum: Ecosystem quality status should be above this threshold, otherwise the water body would lose with high probability aquatic diversity and beneficial use and ecosystems will face severe reduction or complete loss of Ecosystem Services (Category 4).

Table 8.1. Proposed physico-chemical benchmarks for (surface) freshwater ecosystems. Annual average total concentrations, unless otherwise indicated.

Parameter	High Integrity (Category 1)[1]	Extreme impairment (Category 4)
Dissolved oxygen (DO) saturation (%)	80-120	<30 or > 150
Dissolved oxygen concentration (DOC) (mg/l)	7.3-10.9 [2]	<3 or > 13.6 [2,3]
(Optional) BOD_5 (mg/l)	-	>10
Total Phosphorous (TP) (µg/l) - Lakes and reservoirs - Rivers and streams	 <10 <20	 >125 >190
Total Nitrogen (TN) (µg/l) - Lakes and reservoirs - Rivers and streams	 <500 <700	 >2500 >2500
Chlorophyll (µg/l) - Lakes and reservoirs - Rivers and streams	 <3.0 <5.0	 >165 >125
pH	6.5-9.0	<5.0
Temperature	No deviation from background value or reference system or optimum temperature ranges of relevant species	Large deviations from background value or the thermal tolerance range for characteristic species
Un-ionized Ammonia (µg NH_3/l)	15 [5]	100 [5]
Aluminum (µg/l) at pH <6.5 at pH >6.5	 5 10	 - 100
Arsenic (µg/l)	10	150
Cadmium (µg/l) [4]	0.08	1.0
Chromium (µg/l) [4] Cr III Cr VI	 10 1	 75 40
Copper (µg/l) [4]	1	2.5
Lead (µg/l) [4]	2	5
Mercury (µg/l) [4]	0.05	1.0
Nickel (µg/l) [4]	20	50
Zinc (µg/l) [4]	8	50

[1] Natural sources and geographical conditions may cause natural background values that differ from the benchmarks for high integrity. Instead of these benchmark values, natural background concentrations may be used for setting local criteria for high integrity.

[2] Dissolved oxygen concentration varies depending on temperature, pressure and salinity; benchmarks are for freshwater at sea level (760 mm Hg) and 20^0C based on the DO%.

[3] Daily average.

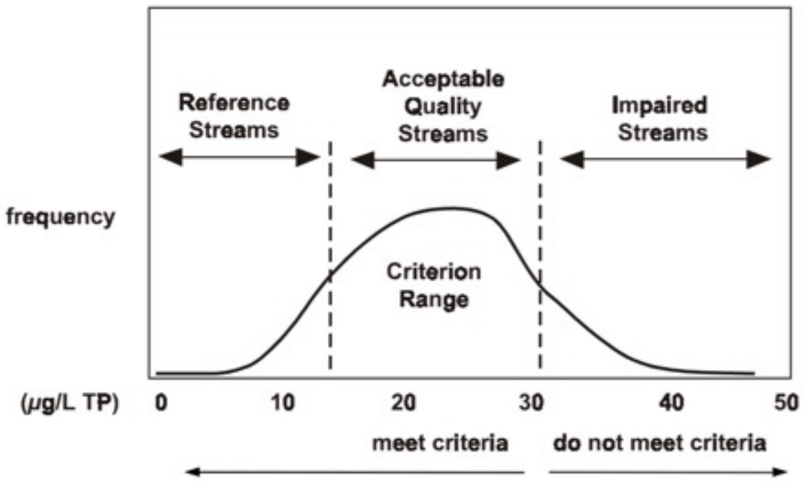
[4] Applicable for waters with low hardness (< 6 mg/l $CaCO_3$). In case of higher hardness, the benchmark values may be somewhat higher.

[5] Corresponding total ammonia (NH_3 + NH_4^+) concentration depend on pH and temperature. At pH 7.5 and 20^0C the benchmarks for total ammonia- N are 1 000 µg/l and 6 641 µg/l, respectively.

Source: UNEP. 2018. A framework for freshwater ecosystem management. Volume 4: Scientific background. Nairobi, United Nations Environment Programme.

As Table 8.1 shows, there is often a grey area between good and highly impaired water quality. Indeed, some criteria depend on other water quality characteristics, such as alkalinity, hardness, pH, suspended solids and salinity, which alter inter alia the biological availability and/or toxicity of certain chemicals (see footnotes for Table 8.1). As a result, water quality varies naturally with a site's specific physical, chemical and/or biological conditions, depending among others on geology and season (e.g. the sediment load is higher after rains than before). This natural variation constitutes a significant challenge for applying 'generic' thresholds to a local context. Thus, for any work with water quality criteria, USEPA (2000, 2008) and UNEP (2018) recommend to first define a natural baseline (Figure 8.2).

Figure 8.2. Frequency distribution divided into high-quality reference streams (baseline), acceptable quality streams and impaired (eutrophic) streams



Source: USEPA. 2000. Nutrient criteria technical guidance manual: Rivers and streams. Washington, DC, Environmental Protection Agency

8.3. Risk mitigation measures

Applying an ecosystem health approach necessitates adopting precaution as a fundamental principle to enable water bodies to provide and secure their respective ecosystem services in a sustainable manner. The precautionary principle contrasts with the "impair-and-then-repair" paradigm, which remains common practice in water resources engineering and development (UNEP, 2018). As water quality monitoring has a low coverage in many regions, a precautionary approach focuses first of all on preventing possible harm, which requires awareness about ecosystem services and downstream impacts. A key advantage of the precautionary approach is that farmers have no need to access laboratories or to understand the water quality parameters discussed above. This also represents an advantage where emerging contaminants such as pharmaceutical residues are concerned, as laboratories in many low-income countries lack sufficient equipment and no thresholds are yet in place to quantify the associated risk.

To prevent erosion and pollution before they impact waterways and water quality, FAO, USDA and many others have developed critical control points (e.g. Table 8.2) and good agricultural practices (Table 8.3). These help avoid over-fertilization, increases in soil salinity and pesticide-related ecological trade-offs, among others (e.g. FAO, 2007, 2010). Similar guides exist for livestock (e.g. FAO & IDF, 2004; FAO & OIE, 2009) and fish farming (e.g. ASEAN, 2015). The spectrum of good practices is vast and requires adaptation to local circumstances and farmer's limitations and opportunities (e.g. in view of the reduction or replacement of chemicals or the availability of plants for hedgerows to reduce runoff).

Table 8.2. Examples of hazards from livestock keeping and corresponding control points

Chemical hazards	Control points
Chemical contamination of environment, feed and water	• Farm location • Animal movement • Use of agricultural chemicals • Feed and water quality • Equipment and building materials • Hygiene practices
Toxins of biological origin (plants, fungi, algae)	• Feed, pasture, and water quality • Farm location • Animal movements • Feed production, storage and • Transport
Residues of veterinary medicines and biologicals (incl. medicated feed and water)	• Treatment of animals • Sales and prescription control • Record keeping • Residue control • Quality of feed and water

Source: FAO & OIE. 2009. Guide to good farming practices for animal production food safety. Rome

Where polluted water leaves livestock or fish farms, on-site water treatment should be considered, for example through the construction of artificial wetlands (Wang *et al.*, 2018). Farmers can also minimize pollution affecting their soil and crop health through low quality irrigation water, by adopting water efficient irrigation practices which minimize the volumes of water needed.
Table 8.3 provides an overview of possible water quality impacts from agriculture on water bodies, and examples of good agricultural practices to avoid or reduce risks for water quality and ecology. Specific challenges for crops and soils and related mitigation measures are also addressed in Chapters 4 and 5 dedicated to pathogenic and chemical risks including salinity.

Table 8.3. Agricultural impacts on water quality and related mitigation options

On-farm activities	Challenges for water bodies	Good agricultural practices for risk mitigation
Tillage/ ploughing	Depending on topography and rainfall, increase of runoff, sedimentation and turbidity: phosphorus and pesticides adsorbed onto sediment particles; siltation of river beds and loss of habitat, spawning grounds, etc.	Minimize erosion and farm runoff through cover crops, mulching, hedgerows, etc., consider zero-tillage.
Fertilizer use and manure spreading	Depending on dosage, slope and soil conditions, possible runoff resulting in contamination of receiving waters with phosphorus and nitrogen, leading to water eutrophication, excess algal growth, water deoxygenation and loss of fish biodiversity), as well as contamination through pathogens and antibiotics from manure. Leaching of nitrates to groundwater potentially threatening public health.	Use locally recommended fertilizer dosages. Prevent farm runoff, for example by building anti-erosion structures and planting grass rows across slopes.
Pesticide application	Runoff of pesticides leads to contamination of water bodies affecting their biota, including possible public health impacts from eating contaminated fish.	Apply Integrated Pest Management (IPM) for pests and diseases, including the use of biological pesticides where possible. Use only locally recommended dosages and prevent farm runoff.
Irrigation infrastructure	Changing the natural patterns of river flow and the creation of irrigation dams can block the movements of fish and affect whole ecosystems.	Adopt environmentally sound standards to make decisions regarding location, type and operation of future reservoirs and dams.

Irrigation water management (effects on farm soils, crops and human health)	Use of low-quality water, such as (diluted) wastewater affecting soil and crop health and potentially consumers; possible bioaccumulation of chemicals in crops or fish. Runoff of chemicals to surface waters or infiltration into groundwater affecting downstream water bodies and communities Too low/high irrigation amounts causing salt accumulation in the rooting zone or groundwater.	Use safe irrigation practices and a multi-barrier approach to minimize contaminant transfer. Prevent uncontrolled drainage. Build natural water filtration or sedimentation infrastructure (wetlands, bunds, ponds, terraces) to maximize on-plot water use (and minimize run-off). Adjust irrigation techniques, intervals and amounts to water and soil salinity, reclamation of saline or sodic soils; use of more resistant crops.
Clearcutting, afforestation and reforestation	Changes in land cover can increase soil exposure, compaction, runoff and sedimentation, alter hydrological flows and provoke a decline in riparian areas affecting water and land quality and biodiversity. Soil compaction limits water infiltration.	Implement anti-erosion measures; ensure the conservation of valuable plants (e.g. fruit trees). Use good silvicultural practices, such as the watershed management module of FAO's Sustainable Forest Management (SFM) Toolbox (FAO, 2017).
Animal husbandry, feedlots, animal corrals and their waste management	Contamination of waterbodies with pathogens (bacteria, viruses, etc.) leading potentially to chronic public health problems. Also contamination by metals, antibiotics and other pharmaceuticals contained in livestock urine and faeces. Potential leaching of nitrogen, metals, etc. to groundwater.	Use chemicals (fertilizers, agricultural and veterinary chemicals, pesticides, etc.). appropriately to avoid contamination of the local environment. Have a waste (water) management system in place. Capture and treat farm off-flow before it enters natural water bodies.
Aquaculture, fish feeding and waste management	Release of pond water with high levels of nutrients (through feed and faeces) to surface water and groundwater leading to serious eutrophication. Within-lake cage farming is considered one of the major stressors on lake water quality. Organic and nutrient loading can easily result in organic accumulation in the sediment with lake water quality deterioration, accelerating the process of lake eutrophication and toxic cyanobacterial bloom. Introduction of exotic species can severely affect local biodiversity.	Use chemicals (fertilizers, agricultural and veterinary chemicals, pesticides, etc.). appropriately to avoid contamination of the local environment. Have a waste (water) management system in place. Capture and treat farm off-flow before it enters natural water bodies.
Aquaculture, fish feeding and waste management	Release of pond water with high levels of nutrients (through feed and faeces) to surface water and groundwater leading to serious eutrophication. Within-lake cage farming is considered one of the major stressors on lake water quality. Organic and nutrient loading can easily result in organic accumulation in the sediment with lake water quality deterioration, accelerating the process of lake eutrophication and toxic cyanobacterial bloom. Introduction of exotic species can severely affect local biodiversity.	Avoid over-feeding/stocking, and observe outflow guidelines for pond effluents. In the example of Thailand (ACFS, 2009), the law requires effluent to be treated prior to discharge. If farm size is over 1.6 ha, the effluent parameters shall meet the following specification: • BOD not above 20 mg/l. • Suspension solid not above 80 mg/l. • NH_3-N not above 1.1 mg/l. • Total Nitrogen not above 4.0 mg/l. • Total Phosphorus not above 0.5 mgP/l. • pH 6.5-8.5 Exotic fish species should not pose a risk to the natural biodiversity and ecosystem health.

Source: Authors' own elaboration

8.4. Adopting good agricultural practices

To facilitate the adoption of good agricultural practices, farmers have to be trained, and their awareness as a community member on upstream-downstream impacts and ecosystem services increased. However, training alone might not translate into behaviour change (Drechsel, Qadir &, Galibourg, 2022). Incentive systems, like payments for environmental services (PES), might be required where without tangible benefits farmers do not accept responsibility for downstream impacts of their actions. What can trigger behaviour change has, however, to be explored in each local context. Another possible incentive for the adoption of good agricultural practices is the increasing availability of national and international certification programmes or schemes. Increasing consumer demand for confidence in safe and sustainable food, and the need among retailers for a dependable tool to evaluate suppliers underline the importance of certification. Such forms of certification can be voluntary or mandatory, as in the case of outgrowers or export crops farmers. Even where voluntary, local farms can request certification of their good agricultural practices. In such cases, farm audits are carried out to ensure that farms are complying with the certification requirements (SFA, 2019; APO, 2016; QUACERT, 2020). Some schemes ask for farm conservation plans (i.e. a written action plan on the conservation of flora, fauna and natural resources in the wider farm area). Certification can provide several benefits for farmers, such as better and easier access to the market and clear agreements and dialogue with retailers. However, where consumers' ecological or risk awareness is low, certification might only reach domestic niche markets but remains an option for export crops (Keraita & Drechsel, 2015).

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Chapter 9

Water quality management in the context of river basins

Hugh Turral

As pointed out in previous chapters, the management of water quality extends beyond the farm, and has to consider upstream and downstream linkages within a catchment or water basin, where agriculture may be both a possible cause and a possible victim of water quality changes (FAO, 2018). This chapter briefly summarizes approaches used to analyse, monitor and manage water quality in its larger geographical context.

9.1. From source to sink

Within a hydrological system, pollution is classically described in terms of sources, pathways and sinks, where pollutants eventually accumulate and cause negative impacts. Easily identifiable sources with relatively high concentrations of pollutants, such as human settlements and industries located at water ways, are known as point sources. Most sources of agriculturally derived pollutants (e.g. agro-chemicals and eroded soils) are more diffuse, with small, episodic contributions across large areas, and are described generically as non-point-source pollutants.

Point-source pollutants from agricultural activities are also generated by intensive livestock and aquaculture units or from large-scale processing of agricultural products (e.g. milk factories, abattoirs and sugar cane mills).

A qualitative assessment of the relative contributions of cropping, livestock production and aquaculture to the generation of non-point source pollutants is given in Table 9.1:

Table 9.1. Relative contribution of agricultural production systems to non-point source pollution

	Nutrients	Salts	Sediments	Pesticides	Pathogens	Metals	Organic carbon	Pharma-ceuticals
Crop production	***	***	***	***	*	*	***	-
Livestock	***	*	**	–	***		***	***
Aquaculture	**	*	–	–	*		**	**

Source: Modified from FAO. 2018. More people, more food, worse water? A global review of water pollution from agriculture. FAO, Rome and IWMI, Colombo

The impacts of pollutant generation may be local or felt many hundreds of kilometres downstream and out to sea (e.g. nitrate runoff effects on coral bleaching in the Great Barrier Reef, Australia) (McCook *et al.*, 2010). Impacts may occur at interim points in the landscape and along hydrologic pathways, where pollutants accumulate, can be absorbed and "neutralised", or also be remobilized and exported downstream. The duration of impacts at such points can be very long, depending on patterns and the continuity of incoming loads and processes governing fixation, possible remobilization and transport downstream. Humans and animals also function as biological sinks, especially for toxins and microplastics that slowly accumulate in the food chain. However, the primary sinks for agricultural and other pollutants are soils, groundwater and the ocean.

The ability to define pollutant pathways between source and impact is essential due to the varying intersections of hydrology and human activity (e.g. food marketing) at different points along the flow paths and food chain. Quantifying these pathways and food consumption provides an opportunity to predict impacts on environmental and human health, and to identify entry points for monitoring and risk mitigation.

A sink, in simple terms, is a point in the landscape or water system where pollutants accumulate and may cause negative impacts. This accumulation may be temporary or permanent, depending on the position in the landscape, the loading, frequency, management, chemical and biochemical transformation, and secondary export of pollutants further downstream. Removing and remediating pollutants is costly and can be hazardous, therefore the most effective and economic approach to managing pollutants is to minimize their generation at source. This can be achieved through water treatment at point-pollution sources or through the adoption of less polluting agricultural practices in areas known for non-point pollution.

The impacts of agricultural pollution range from environmental degradation to health risks and industrial costs that are often borne by society as a whole. These include:

- water treatment costs (protecting public and environmental health);
- market costs on agricultural production (mitigating lowered productivity);
- non-market and market costs on fishing (damaged habitat, migration to better habitats and lowered productivity);
- market costs on industry (sediment, salt and others);
- market costs to hydropower and dam operators (sediment removal);
- non-market costs on recreational and amenity uses.

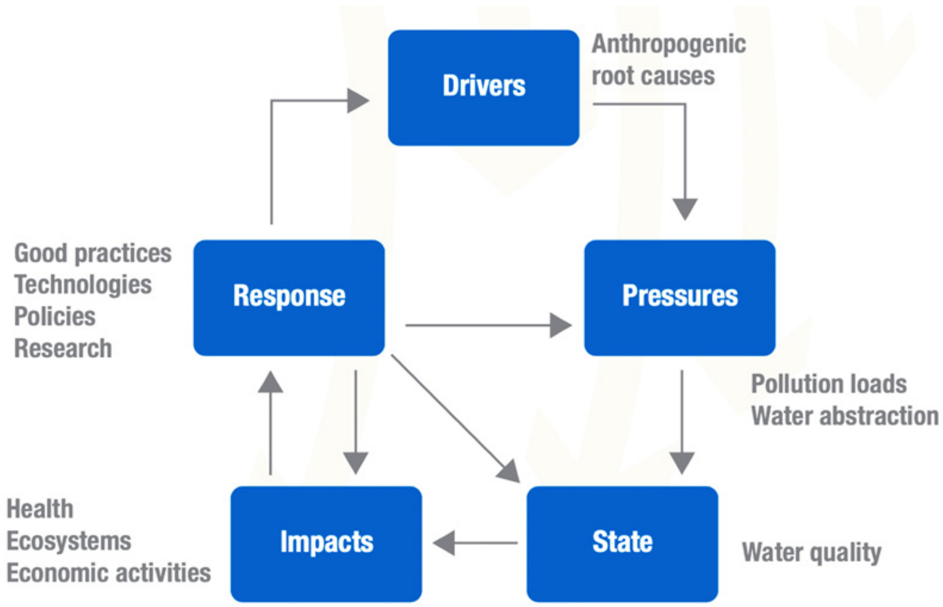
9.2 Adaptive pollution management across scales and sectors

One of the main challenges associated with managing pollution from human activities in a larger geographical context is the need to link preferences and perceptions with human actions and the consequent impacts on ecosystem services and health. One example is the (perceived) need of hillslope farmers to burn their fields, which can heighten runoff and siltation of downstream reservoirs used for irrigation or hydropower. An integrated management response ideally links scales, sectors and stakeholders, combining social and biophysical perspectives and their dynamics over time and scale. Such issues can be termed complex or "wicked" problems (Patricio *et al.*, 2016). Two common approaches to address this challenge are the DPSIR (Drivers, Pressures, State, Impact, Response) concept at the conceptual level and AM (adaptive management) at a more operational level.

9.2.1. DPSIR

The DPSIR concept helps develop an understanding of human impacts on natural systems. It was adopted by the EU as part of the Water Framework Directive (European Commission, 2000) and has been recommended more broadly for developing countries (FAO, 2018). The concept provides a logical connection between the various components of cause and effect in pollution, in general, and encompasses management of water quality from field to ocean (Figure 9.1). It has been widely used to transform unstructured problems into ones that can be effectively addressed within a broader analysis for longer-term management of ecosystem-society dynamics, needs and trade-offs. This approach works best when there is sufficient understanding of all biophysical processes, as well as the required data and techniques to quantitatively combine biophysical and socio-ecological information within a given or changing political economy.

Figure 9.1. DPSIR cycle and connections



Source: Modified from European Commission. 2002. Guidance for the analysis of pressures and impacts in accordance with the Water Framework Directive. Common Implementation Strategy. Working Group 2.1. Brussels, Office for Official Publications of the European Communities

Table 9.2. The DPSIR framework: terms and definitions

Term	Definition
Driver	An anthropogenic activity that may have an environmental effect, such as agricultural intensification or a change of diet.
Pressure	The direct effect of the driver on water quality (e.g. higher siltation rate through increased erosion).
State	The resulting condition of water quality (i.e. physical, chemical and biological characteristics).
Impact	The effect of the water quality change on environmental health including human and aquatic life.
Response	The measures taken to improve the state of the water body.

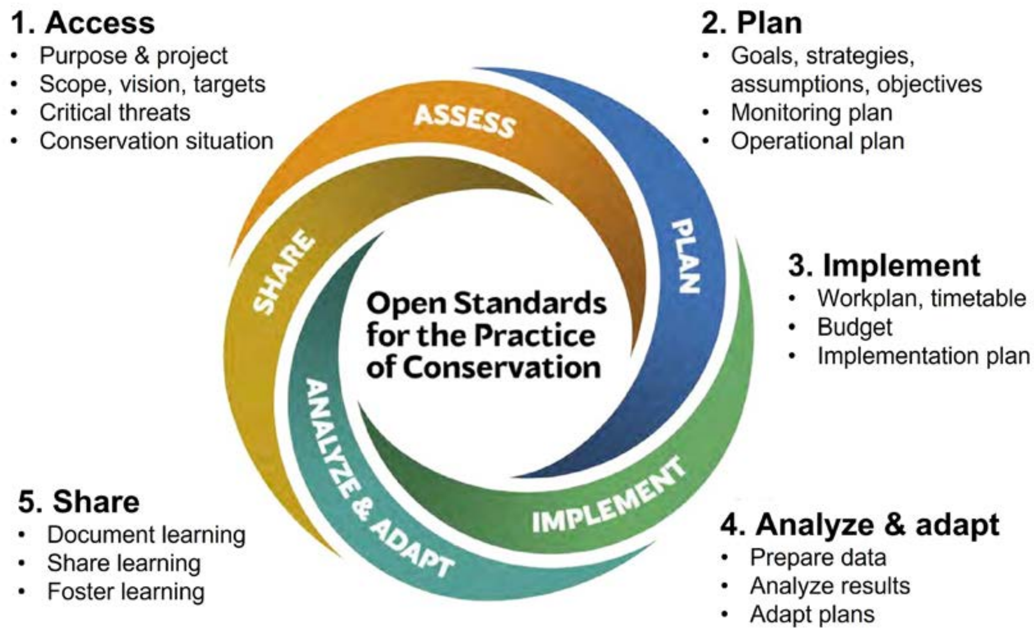
Source: Modified from European Commission. 2002. Guidance for the analysis of pressures and impacts in accordance with the Water Framework Directive. Common Implementation Strategy. Working Group 2.1. Brussels,Office for Official Publications of the European Communities

9.2.2. Adaptive management

Adaptive management (AM) underpins sustainable natural resource management strategies in countries such as Australia, New Zealand and the United States. It recognizes that responses to address one set of problems may provoke unforeseen outcomes, synergies and impacts, and that coherence in policy, strategy, planning and practical activities is an iterative and often cyclical process. AM is used by communities, state authorities and independent service providers, although many examples in the literature focus on a single issue and rely heavily on data and modelling.

AM is also often described as a cyclical process, as shown in Figure 9.2, following classic expressions of the strategic management cycle, with a strong focus on learning and adaptation. It can help to address the challenges and needs identified in the DPSIR analysis from a practical perspective. An example of AM in the wastewater and sanitation sector is 'sanitation safety planning' (WHO, 2022).

Figure 9.2. An example of the adaptive management cycle in the context of environmental conservation measures



Source: CMP. 2020. Open standards for the practice of conservation: Version 4.0. The Conservation Measures Partnership (www.conservationmeasures.org)

AM is designed to address uncertainty or disagreement about underlying system dynamics or the expected effects of management and is useful when management decisions are taken over a time frame long enough to generate learning for feedback (Williams & Brown, 2012). Models can play a key role in dealing with this complexity by representing uncertainty in the description of a system and its components, dynamics and likely responses to management. The rapidly expanding set of modelling approaches include Multi-Criteria Decision Analysis (MCDA) (Gregory *et al.*, 2012) and the use of agent-based modelling in conjunction with a creative analysis of human preferences and perceptions, for example the Challenge and Reconstruct Learning (ChaRL) framework (Smajgl *et al.*, 2015). Models based on available data, concepts and beliefs can be built to predict scenario outcomes, design monitoring programmes to test those outcomes, and then compare and modify active management strategies. Scenarios can be built to represent opposing opinions or understandings and can identify supporting research and data needs as well as interventions that will generate learning and management feedback. For adaptive decision making, government agencies must transition from a traditional "top down" organizational structure to one that is more collaborative, risk tolerant, inclusive and flexible (Williams & Brown, 2012). This requires explicit community involvement in the identification of problems and solutions (Box 9.1), and is in some ways less centralized than the expert process of DPSIR.

It should be noted that most examples are found in data-rich countries, where spatial and temporal data (e.g. monitoring in-stream water quality changes over time) can be mapped within the watershed using GIS. The Wisconsin Department of Natural Resources (DNR), in the example below, offers a suite of six physically based models for management of agricultural and urban-sourced phosphorus at different scales, which require comprehensive primary and secondary data and technical/laboratory support. The Wisconsin guidance also provides considerable detail and references for a suite of best management practices (BMPs) ready for different contexts (urban and rural catchments) as well as for arable, livestock and mixed farms.

The challenges for AM in developing countries are considerable in terms of costs, the availability of data, information, technical and organizational support from "government", and the capacity and motivation in communities to tackle these issues beyond managing their own needs.

Box 9.1. Examples of adaptive management approaches

The following two examples describe the key steps of an AM plan. The first example concerns the management of pollutants and water quality according to the Australian Water Quality Management Framework of which the key steps are outlined below (Water Quality Australia, n.d.):

1. Examine current understanding
2. Define community values and management goals
3. Define relevant indicators (ecosystem condition, pollutant loads, input use)
4. Determine water/sediment quality guideline values
5. Define draft water/sediment quality objectives
6. Assess if draft water/sediment quality objectives are met
7. Consider additional indicators or refine water/sediment quality objectives
8. Consider alternative management strategies
9. Assess if water/sediment quality objectives are achievable
10. Implement agreed management strategy.

The second example presents the key steps of an AM plan to limit phosphorus exports from a catchment in Wisconsin, US (Wisconsin Department of Natural Resources, 2013). The purpose is to improve water quality within watersheds and receiving surface water bodies to eventually comply with state in-stream phosphorus targets and standards.

1. Identify representative partners (from all stakeholders)
2. Describe the watershed and set load reduction goals in line with state standards
3. Conduct a watershed inventory and identify critical source areas
4. Identify where reductions will (or can) occur
5. Describe management measures to be implemented at different sites
6. Estimate load reductions expected by permit term (load reduction target)
7. Measuring success
8. Financial security
9. Implementation schedule with milestones.

9.3. Modelling and decision support

The previous section and the example of phosphorus management in Wisconsin indicate the central importance of simulation modelling in evaluating and testing water quality management strategies and actions. It is difficult to observe all components of complex hydrological cycles and the processes that govern the transport of solutes and particles through land and water systems.

Models approximate these processes to varying degrees and substitute or augment observations but they cannot replace observation; and the more sophisticated a model, the more intensive the requirements for data, as well as for calibration and validation: there is little point in predicting the outcomes of future management activities if a model cannot replicate current and historic conditions.

Regardless of scale, the key processes to be modelled for water quality management begin with the hydrologic cycle and the pathways and flows of water through soil, groundwater, open channels and open water bodies. The transport of solutes is modelled by advection and dispersion, mediated by chemical models of sorption, desorption and chemical reactions, and changes in soils and suspended particles. Sediment transport in surface water flows is a complex process but can be modelled simply in relation to hydraulic (slope, bed condition, flow rate) and material characteristics (particle size and type).

On farms, the physics of the underlying processes are modified by management practices. For example, in order to determine the likely export of nitrogen from fertilizer application, it is necessary to consider the type of fertilizer, the timing and rate of application, the rainfall before during and after application, soil type and physiographic conditions (slope, uniformity), irrigation application (amount, method, duration, excess as drainage) and whether fertilizer is incorporated or broadcast.

At catchment scale and above, the impacts on an aquatic habitat or the state of a water body are influenced by many factors, which also require observation and research to understand the process and quantify cause and effect. The formation of algal blooms in water ways and along coasts is a good example, especially where less common toxic algal blooms form that kill fish, aquatic fauna and livestock. Multiple pollutants (N,P, sediment) are key factors but do not cause blooms without the right mix of enabling conditions of temperature, flow rate and flow depth, salinity and BOD. Furthermore, the activities that generate low flows could be natural or due to excessive diversion of water for other uses (irrigation) or a combination of the two. Similarly, sediment could be generated by forest clearance, the aftermath of a fire, construction activity, or be a consequence of rainfed or irrigated cropping.

Over recent decades, research has contributed to the development and use of models by understanding and parameterising fundamental processes, and through developing new techniques and instrumentation to record the required data. Hydrological models have increased in complexity and effectiveness at the "cost" of data demands over time and space. In most developing countries, the institutional capacity exists to build, refine and use models for water quality management, but contemporary data collection, coverage and availability, as well as data transmission and storage, are typically problematic and require further investment and attention.

Table 9.3 attempts a broad summary of the types of modelling, their purposes and data requirements, and examples of software, with some comments on their appropriateness for application under low developing country (LDC) conditions. A more comprehensive compilation of models for water quality simulation can be found in FAO (2018); however, socio-hydrological models that combine or link biophysical and socio-economic indicators to better understand the human-water system in a holistic sense remain a challenge (Blair & Buytaert, 2016).

Table 9.3. Examples of models for managing water quality by scale, purpose and data needs

Model scale	Model purpose	Model types	Data requirements	Applicability in LDCs	Examples of software
Farm management	Management of constraints: salinity, waste-water quality, incoming non-point source pollutants	Salinity balances Nutrient balances Static lumped models Dynamic process models	Local sampling and analysis Record keeping Survey and sample data Detailed soil, water, atmosphere parameters*	**High** Possible via student work (local universities)	Water Productivity Function (WPF) model, NUTMON, MOPECO-Salt, SWAP, DSSAT, APSIM, SaltMod
	Management of agronomic inputs and minimization of exports: N, P, sediment, pesticides, salt	Nutrient budgets production function models, Crop-soil-water models • Point • Spatial	Yield records, prices, "efficiencies". Detailed soil, water, plant, atmosphere, data: primary and secondary.	**High** Consultants and governmental institutions	LIMDEP, SWAP, DSSAT, APSIM
Integrated river basin and coastal zone management	Formation, persistence and dynamics of eutrophic conditions in estuaries, coastal zones and the ocean	Complex integrated models – surface and groundwater hydrology, coupled with coastal hydraulic models and solute and sediment transport models linked to ecological models and socio-economic factors	Extensive – the data needs of all component models plus coastal data on undersea topography, currents and flows, wind, tides, salt-freshwater mixing. At a minimum, "simple" regression models of algal growth	**Limited** Challenging for normal research purposes; specialist support needed	Mike 21 FM-ECOLab
Principal agent modeling; game theory	Human action and preferences: managing conflicting stakeholder needs	Scenario modelling Risk modelling Decision support systems	Extensive social survey and or stakeholder meetings.	**High** Generally undertaken through academic/ research cooperation	Challenge and Reconstruct Learning (ChaRL), Multiple-criteria decision analysis (MCDA), Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)

Source: Author's own elaborations

9.4. Options for data-scarce regions

Data availability for modelling remains a challenge in many parts of the world, highlighting the need for alternative approaches for evidence-based basin-wide water quality management.

9.4.1. Geographical Information Systems (GIS) and remote sensing

Over the past 20-30 years, the emergence of GIS and remote sensing have had a profound impact on the ability to map, undertake simple processing of limited spatial and temporal data, and determine changes in the state and trends of natural anthropogenic processes.

GIS has been widely adopted throughout the developing world, where extensive capacity exists to establish and maintain such systems and process the data. Many simple modules for specific analysis are available commercially and as open-source tools.

Remote sensing data can provide effective estimates of some forms of data (Table 9.4), especially in relation to improving the description of catchments, river basins and stream networks. Remote sensing provides consistent spatial and temporal coverage of land surface characteristics and can infer environmental conditions such as algal content, soil moisture and salinity in conjunction with field validation.

Table 9.4. Remote-sensing applications in water quality management

Category	Application	Type of data*	Resolution	Focus
Catchment and river basin management	Catchment delineation (DEM, stream paths, water bodies)	SRTM, VNIR and Interferometric SAR data	~10 m (Sentinel) to 1 km (MODIS)	Base maps for 1) monitoring and 2) catchment model parameterization
	Land cover classification Infrastructure mapping	VNIR, SWIR, Pan SAR	10 m to 1 km (free data)	
	Phytoplankton/algal bloom mapping in streams and water bodies	VNIR, SWIR (Sat) Hyperspectral (Airborne/UAV)	10 m to 1 km (free data) 3-30 m	Monitoring Research
	Sediment mapping in rivers, freshwater bodies, estuaries, CZ	VNIR/SWIR (Sat) Hyperspectral (Airborne/UAV)	10 m to 1 km (free data) 3-30 m	Monitoring, model calibration Research
	Salinity mapping	(VNIR/SWIR) Hyperspectral	10 m to 1 km (free data) 3-30 m	Water balance components in hydrological models /calibration Interpolation of ground data
	ET estimation Rainfall	VNIR +TIR Geostationary instruments – TRMM, GMS	30 m to 4 km	Management, monitoring. Dryland salinity monitoring/trends Research
Environmental Management	Habitat delineation, dynamics and composition	VNIR, SWIR, SAR Hyperspectral	10 m to 1 km 30 to 90 m 3 to 30 m	Project studies and research Research
	Pollutant load estimation (N, P)	Hyperspectral	3 to 30 m	Model parameterization and research
Field applications – farming	Soil mapping, crop mapping, crop health/ NPP; irrigation monitoring	VNIR/SWIR/TIR**	1 m commercial to 10 m (Sentinel) – 100 m (LS 8 TIR)	Precision agriculture (fertilizer and pesticide management; irrigation scheduling and management) System performance assessment
	Soil Salinity Assessment	VNIR Hyperspectral***	1 m commercial 10 m to 1 km (free data) 3 to 30 m	(Farming, system planning) and modelling Research
	Crop productivity and water use	VNIR/SWIR correlation to vegetation indices VNIR/SWIR/TIR energy balance	1 m (commercial) to 10m + (free) 30 m to 100 m	Commercial management services Water rights adjudication Research

* SAR: Synthetic aperture radar; SRTM: Shuttle Radar Topographic Mission (90 m global DEM); SWIR: Short Wave Infrared; TIR: Thermal infrared, used in ET and NPP/Yield estimation; TRMM: Tropical Rainfall Measuring Mission, GMS: Geostationary Meteorological Satellite;UAV: Unmanned aerial vehicle (drone); VNIR: Optical remote sensing in the Visual (Red, Green, Blue) and Near-Infrared wavebands
**VNIR/SWIR/TIR data – increasingly available for free at useable resolutions (10 m to 5 m with Pan sharpening and other interpolation techniques) – processed or with accessible online processing (GEE).
*** All hyperspectral data have an associated cost of flying an aeroplane or UAV, as there is no Hyperspectral Satellite in orbit at the moment. Coverage by Hyperion (the only hyperspectral satellite to have been in orbit) was very selective with a narrow field of view (18 km swath width).

Source: Author's own elaborations

Case study 6 in the annex presents a range of salinity mapping projects and programs realized in Australia.

9.4.2 Citizen science approaches

As outlined above, the involvement of basin stakeholders in analysing upstream downstream water quality challenges and possible solutions is central to any basin-wide management approach. This involvement can extend beyond decision-makers. Involving citizens in data collection has the potential to increase data, create awareness about water quality issues and help in the formulation of citizen-backed community action plans (UN Water, 2018; Quinlivan, Chapman & Sullivan, 2020). Such an approach can also help overcome possible disconnection between civil society and its institutions and/or complement the efforts of authorities, which might not have sufficient capacity to monitor water quality in vast basins.

The underlying idea is that citizens hold immense potential to increase temporal and spatial data availability, and therefore could bridge existing data gaps while enhancing their awareness of environmental issues (Carlson & Cohen, 2018; Walker *et al.*, 2016; Buytaert *et al.*, 2014). However, citizen-derived data may also be selective and biased, requiring attention to effective design principles for successful citizen science projects (Brouwer *et al.*, 2018; Crall *et al.*, 2011). When well-designed, citizen science projects have been very successful in analysing pollution (Capdevila *et al.*, 2020), for example through adopting biological water quality indicators, ranging from insects to the incidence of aquatic pests in fresh water systems, or the use of simple water quality test kits in school programmes (Ballard, Dixon & Harris, 2017) to generate data and increase awareness about catchment health and resilience.

In order to harness the rising enthusiasm from a wide range of participating groups, citizen science projects should go beyond data collection and try to understand social change models with the ultimate aim of developing community-driven water quality solutions. In South Africa, for example, a suite of tools was packaged into an integrated water resource and catchment monitoring toolkit, known as "Capacity for Catchments", for roll-out within South Africa and neighbouring countries (Graham & Taylor, 2018).

The development, and in some cases, the adaptation of the tools was based on the review and assessment of key water resource types, such as rivers/streams, wetlands, estuaries, springs and rainfall. This resulted in the following tools:

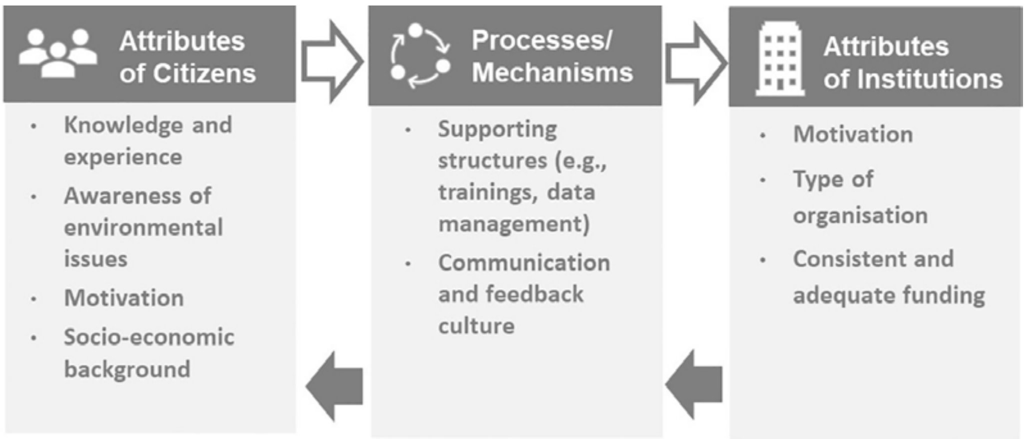
- Aquatic Biomonitoring including an associated phone Apps
- The Riparian Health Audit
- The Water Clarity Tube
- The Transparent Velocity Head Rod
- The Wetland assessment tool
- The Estuary tool
- The Spring tool
- Weather monitoring tools, including Citizen Science Rain Gauges
- The Enviro Picture Building game to investigate catchment issues.

School lesson plans were developed as a component of the toolkit and these materials were integrated into the school curriculum (Graham & Taylor, 2018).

Many of such tools allow for web-based monitoring to share and compare data, including the use of mobile phones. For example, Smart phones for Water (S4W) in Nepal (Davids, 2019) mobilizes a combination of young researchers, citizen science and mobile technology to generate water data. S4W's citizen scientists use an Android phone application called Open Data Kit or ODK to collect data about water (including flow gauging, sediment and water quality). GPS readings and cameras were used to verify the reliability (and error rate) of citizen science observations. All data collected by S4W are open source and freely available (https://data.smartphones4water.org).

Based on a literature review, Capdevila *et al.* (2020) identified three sets of factors for successful citizen science projects in water quality monitoring (Figure 9.3): (i) the attributes of citizens (knowledge and experience in collecting data, awareness of environmental problems, motivation and socio-economic background), (ii) the attributes of institutions (motivation, type of organization, consistent and adequate funding), and (iii) the interactions between citizens and institutions (supporting structure, communication and feedback).

Figure 9.3: Factors steering the success of citizen science projects for monitoring water quality



Source: Capdevila, A.S.L., Kokimova, A., Ray, S.S., Avellán, T., Kim, J. & Kirschke, S. 2020. Success factors for citizen science projects in water quality monitoring. Science of the Total Environment, 728: 137843.

Motivation was also highlighted as a key challenge in the smartphone study in Nepal, where different approaches were tested for different target groups. According to Davids (2019), an important aspect of sustaining citizen science efforts is funding: all efforts to minimize the costs per observation (CPO) while maintaining data quality will lead to lower funding requirements and greater chances of sustainability. In this case, incentives seemed to motivate students to participate in citizen science projects, including (i) the opportunity to use data for their research projects (e.g. bachelor's theses); (ii) lucky draws (i.e. raffles or giveaways); and (iii) receiving certificates of involvement. However, student turn-over remains an issue that needs addressing, and in rural areas with limited student populations and relatively low scientific literacy levels, payments may be the most effective near-term incentive to ensure continuity of observations over time.

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Chapter 10

The cultural, economic and regulatory environment affecting the adoption of marginal quality water and risk reduction measures

Francisco Alcón and Pay Drechsel

Water resources are becoming increasingly scarce around the globe, both in quantity and quality. This trend underscores the need to adopt water supply and demand management alternatives to cover the food needs of a growing population and to lessen the impacts of droughts and heatwaves (FAO, 2018).

The use of marginal quality water (MQW) – like saline water or wastewater for irrigation – offers such an alternative (Qadir *et al.*, 2007) although more often involuntary than planned. Globally, more than 75 million ha of farm land are affected by human-induced salinization, more than 50 percent of which occurs in irrigated landscapes (Sakadevan & Nguyen, 2010). In addition, informal use of wastewater-polluted irrigation water takes place on about 29 million ha downstream of urban centres where wastewater treatment capacities are insufficient or absent (Thebo *et al.*, 2017). Conversely, conscious use of treated wastewater (reclaimed water) to tackle water scarcity is used on less than 1 million irrigated ha (Drechsel, Qadir & Galibourg, 2022). The implication is that any discussion on the enabling environment of MQW use should not only address its promotion in line with the Sustainable Development Goal 6, but also the common reality of ongoing use and related environmental and health hazards.

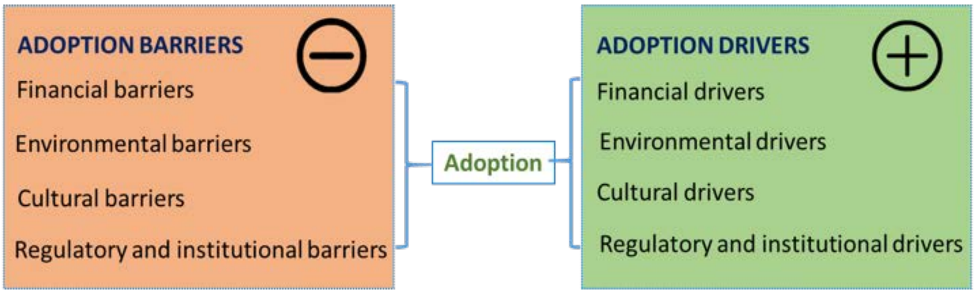
The economic, environmental, socio-cultural and regulatory implications of e.g., planned versus unplanned wastewater use differ in many respects although they converge around the need for safety and behaviour change. For example, education and awareness creation as well as incentive systems are often needed to promote the use of reclaimed (safely treated) wastewater and address reluctance or hesitation among potential users, especially when conventional water sources remain available. On the other hand, where no treatment capacities and alternative water sources to polluted irrigation water exists, awareness creation about the possible risks and/or incentive systems for adopting safety measures should have the highest priority. In both cases, financial considerations vis-à-vis public and private health concerns might influence adoption, while in the case of salinity the primary factor is usually the financial investments needed to prevent loss of farm land.

This chapter provides guidance on how to facilitate adoption of the technical solutions and risk mitigation measures presented throughout this publication, taking into account financial, environmental, social and regulatory-institutional adoption barriers and drivers. It also considers internal factors such as the need for behaviour change and external environmental factors such as policies or the availability of technology (Favin, Naimoli & Sherburne, 2004; Drechsel, Otoo & Hanjra, 2022).

The identification of driving forces and barriers to the adoption of MQW can facilitate the choice of existing risk mitigation measures or incentives tailored to the specific biophysical and institutional context as well as farmer's ability to invest. It also enables feedback for the design of required institutional policies, incentive systems or alternative technical options which could have better adoption potential.

This chapter therefore aims to provide a brief overview of drivers and barriers affecting the adoption of MQW by farmers. To this end, previous water reuse experiences provide insights and examples of site-specific factors affecting adoption decisions, following a basic conceptual framework (Figure 10.1). The framework is applied to the three scenarios of MQW adoption: (i) the use of reclaimed (safely treated) wastewater where freshwater is becoming scarce, (ii) risk mitigation practices where polluted water is already used in the absence of any alternative, and (iii) soil salinity mitigation measures.

Figure 10.1. Conceptual framework of barriers and drivers to adoption

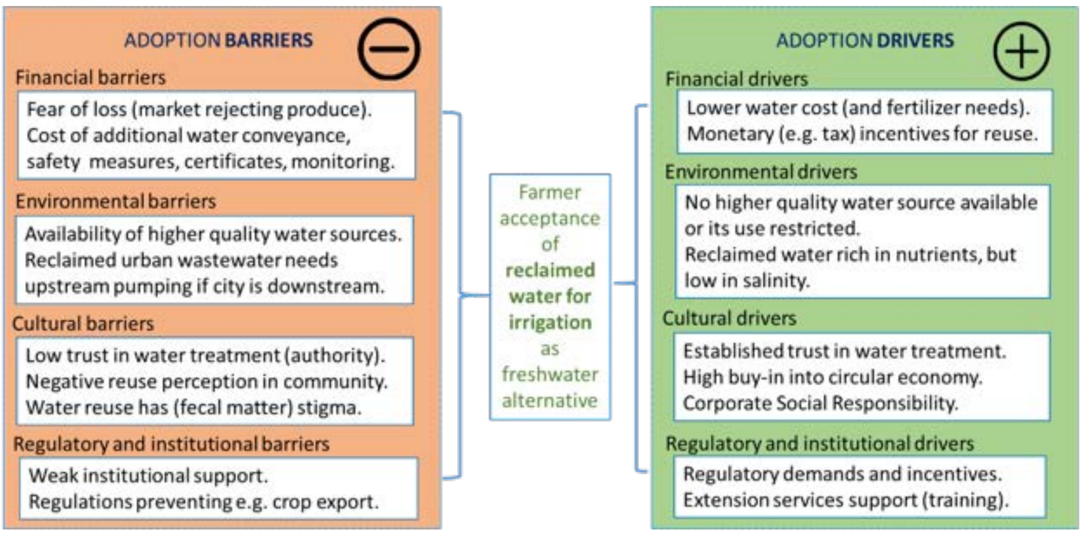


Source: Authors' own elaboration

10.1. Factors affecting the adoption of reclaimed wastewater as an alternative water source

Farmers' acceptance or rejection of well treated (reclaimed) wastewater is influenced by location-specific cultural, religious and socio-economic conditions, as well as water costs, the structure of irrigation networks and cropping patterns (Ganoulis, 2012). However, social factors have been recognized as the main challenges to more effective water management compared with technical factors (Ricart, Rico & Ribas, 2019). Moreover, reuse often offers non-market benefits which justify its implementation, as they exceed the average treatment costs (Alcon *et al.*, 2010, 2012). In many countries, adoption barriers refer to perceptions and can be overcome by designing proper awareness campaign or educational initiatives (Figure 10.2). The relationship between barriers to adopting reclaimed water and options to address them are described in the next sections.

Figure 10.2. Adoption drivers and barriers for the acceptance of treated wastewater as an alternative irrigation water source



Source: Authors' own elaboration

10.1.1. Financial factors

Where both freshwater and reclaimed water are available, farmers may opt to use reclaimed water only if it is offered at a lower price or free, the quality is unquestionable and its use is accepted by society. However, the willingness to accept reclaimed water is growing in line with water scarcity (Deh-Haghi *et al.*, 2020). In some instances, farmers are asked to release their freshwater rights for higher quality use (industrial and urban needs) in exchange for reclaimed water. In these cases, a higher volume obtained than released and the higher reliability of wastewater supply can constitute important incentives. Other possible incentives include subsidies for irrigation equipment or lower taxes linked to the adoption of a freshwater-saving alternative, drawing on mechanisms such as the Green Climate Fund.

Where reclaimed water is made available to farmers, the absorption of additional costs for water conveyance and monitoring must be agreed on between the provider and the farming community (Pistocchi *et al.*, 2018). However, as long as farmers have an alternative water source it will be difficult to charge them or the community for water treatment costs. On this basis, a comprehensive cost-benefit analysis is recommended (Alcon *et al.*, 2013; Winpenny, Heinz & Koo-Oshima, 2010) to determine the gains and costs for the different sectors involved.

10.1.2. Environmental factors

Where reclaimed water has a negative image, the most significant environmental barrier to its acceptance by any sector is the continuing availability of freshwater. In such contexts, MQW sources are deemed a viable alternative only when and where freshwater (surface and groundwater) becomes scarce and expensive (Drechsel, Mahjoub & Keraita, 2015). Another barrier can be the quality of the reclaimed water which might suit some reuse options (or crops) but not others. Where untreated wastewater should be replaced by treated wastewater, a particular challenge can be a preference among farmers for (nutrient richer and/or less saline) untreated wastewater (Hanjra *et al.*, 2018). Finally, providing farmers with wastewater can be topographically challenging and costly in pumping terms, especially where cities are situated in lowlands and farms upstream.

As reclaimed water can requires the introduction of alternative farm management practices, capacity-building programmes will be essential, for example to implement a water quality monitoring program.

10.1.3. Cultural factors

Cultural factors and perceptions play a dominant role in the adoption of reclaimed water. These may include religious considerations but are more often founded in (lack of) education and risk awareness vis-à-vis trust in alternative water sources. Interestingly, such negative perceptions are found more often in the community than among farmers (Ricart, Rico & Ribas, 2019) – and language can play an important role in this regard (Box 10.1). Other adoption criteria are more of agronomic or technical in nature, such as the compatibility of the reclaimed water with site-specific irrigation technology, soil and crop requirements. For example, wastewater may be saline and subsequent treatment (via pond systems) may increase its salinity further, which might not support crops grown for the local market. Conversely, the wastewater might have a significant nutrient load, allowing farmers to save on fertilizers (Drechsel, Otoo & Hanjra, 2022).

Box 10.1. The role of language in the adoption of treated wastewater
In any community programme, care must be taken to avoid the use of negative language and images that could stigmatize wastewater use, and instead identify and use locally appropriate language. For example, terms such as "treated wastewater" may hinder unbiased thinking and generate fear, stigma and disgust. Similarly, technical terms such as "reclaimed water" might not support adoption, while alternative terms such as "recycled water" may trigger more positive reactions (Ricart, Rico & Ribas, 2019). More terminological options should be explored in cases where the reclaimed water is augmenting freshwater and/or desalinated seawater.

There is a general consensus that to achieve widespread acceptance of planned wastewater use schemes, especially in a social environment with the power to influence implementation, it is important to ensure active public involvement from the outset – from the planning phase through to full implementation (USEPA, 2012; WHO, 2006). Public involvement begins with early contact with potential users and can involve the formation of an advisory committee, and public workshops on the rationale, benefits and risks of reuse. In addition to creating trust among farmers, the water source has to be accepted by the market. Thus, any awareness creation programmes must target the community at large, including consumers, with a view to addressing their concerns (Parris, 2011; Mateo-Sagasta & Turral, 2018). Media involvement and the use of positive language are key components as can be seen from the case of Jordan (Box 10.2). The Tunisian case study 7 in the annex re-emphasizes the importance of close stakeholder involvement for successful reuse projects.

Box 10.2. Multi-media reuse promotion in Jordan
Jordan succeeded in informing and convincing its population about the importance of wastewater use in agriculture by implementing an active educational campaign with strong community outreach. Key components included the dissemination of newsletters and guidebooks, the coverage of water issues in newspapers and on television and radio, dedicated websites, and the education of land-use decision-makers. In addition, targeted educational materials were distributed in schools, universities and libraries. As in Kuwait and Tunisia, religious concerns regarding the use of wastewater were expressed, but were not among the top reasons cited by farmers for their reluctance to use reclaimed wastewater for irrigation (Drechsel, Mahjoub & Keraita, 2015).

10.1.4 Regulatory, institutional and policy factors

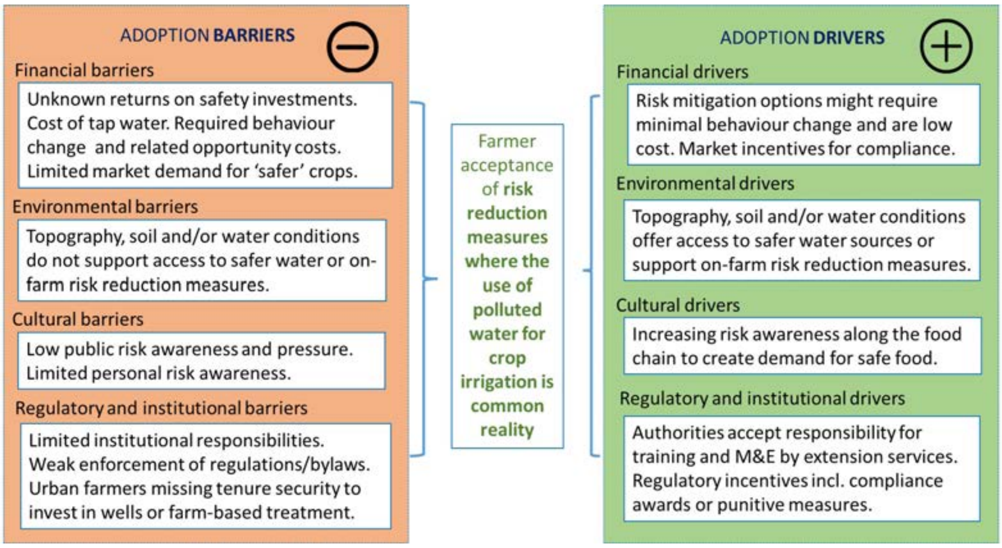
Political and regulatory norms affecting farmers can influence decisions around the adoption of MQW in several ways. These might include crop restrictions that have significant financial implications (Kampa *et al.*, 2011), or instruments such as tax havens, waivers on duties, subsidies or green tariffs that support the use of alternative water sources (Di Mario, Rao & Drechsel, 2018).

National or international water quality criteria for the use of reclaimed water must be adopted to monitor water quality. However, where crops might be exported, it is important to ensure compliance with the criteria in importing countries. International frameworks for water reuse and related quality standards (e.g. European Commission, 2019; Council of the European Union, 2020) can help creating common water quality reuse protocols.

10.2. Factors affecting the adoption of risk mitigation measures where farmers use unsafe irrigation water

In many urban and peri-urban areas of (mostly) developing countries, water bodies may be polluted to varying degrees, while constituting the only available irrigation source for thousands of farmers. In such regions not only are treatment capacities limited, but the level of risk awareness, institutional responsibilities and enforcement of public health regulations are often correspondingly low (Figure 10.3). In the absence of greater risk awareness among farmers and consumers, there will be little incentive to change business as usual. In fact, some farmers might be unaware of the pathogenic risks posed by unsafe irrigation water, instead considering the water rich in nutrients. Consequently, any attempt to implement the WHO-FAO-UNEP guidelines on risk reduction between farm and fork (WHO, 2006) e.g. based on the Sanitation Safety Planning manual (WHO, 2022) must start with increasing risk awareness at multiple levels. This includes institutional capacities, as "wastewater irrigation" is often an informal sector with limited institutional attention and support.

Figure 10.3. Adoption drivers and barriers for the acceptancE of risk mitigation measures where irrigation water is heavily polluted due to the lack of wastewater treatment capacities



Source: Authors' own elaboration

10.2.1. Financial factors

At the farm level, the adoption of safety practices promoted by FAO, such as drip irrigation, requires investments which farmers might not be able to afford. Additionally, cropping restrictions might have a significant impact on farm finances if there is no market for the permitted crops. Other changes in irrigation timing or watering practices might not have financial implications but require knowledge and behaviour change. Without appropriate risk awareness or a clear incentive, such behaviour change carries opportunity costs.

A central challenge for any safety investment on farms or by traders is the uncertainty of market demand from risk-aware customers, regarding their willingness to pay a premium for the extra investments needed to produce safer food. At present, public risk awareness is low, and the educated market is still too small to change production at scale. The main criteria for buying irrigated vegetables or fruits remain their appearance and low price, not their origin, type of water used or other food safety criteria (Keraita & Drechsel, 2015). This situation makes an integrated approach to awareness creation for both farmers and consumers essential or alternative strategies to change behaviour (see 10.2.3).

Another option for the government could be to invest at the community level in treatment facilities and sewerage networks, and to subsidize the additional costs faced by farmers to maintain irrigation safety standards via the (waste)water bill.

10.2.2. Environmental factors

Farm-based risk mitigation measures exist that farmers can adopt where wastewater treatment is absent; however, these are not generic and have site-specific limitations. For example, recommended crop species that pose a lower health risk to consumers might not grow locally, or recommended irrigation systems may not be supported by the slope of the terrain or the quality of the water (e.g. drip clogging). Recommendations must therefore be farm-specific and will require extension services trained in MWQ challenges and risk mitigation options (e.g. FAO, 2019) to facilitate adoption. The alternative use of safe tap water has cost implications, might be unreliable, and under increasing water scarcity also forbidden.

Where different water sources are available but none are sufficient, the joint use of MQW and clean freshwater can provide win-win scenarios in terms of quantity, quality and reliability.

Where technological solutions are adopted and water use is safe, positive externalities include reduced pressure on local freshwater resources and food production, and employment creation (Birol, Koundouri & Kountouris, 2010), which in turn generates important non-market benefits (Alcon *et al.*, 2010). In many areas, land-based water "treatment" by irrigating farmers might absorb more water than official treatment plants (Lydecker & Drechsel, 2010). Internalizing these externalities can help policies to support the investment in awareness creation and training, and incentivize farmers through result-based payments (Sidemo-Holm, Smith & Brady, 2018).

10.2.3. Cultural factors

Among cultural factors, (limited) health education and related risk awareness among farmers are critical factors for the adoption of safety measures. Limited risk awareness applies in particular to the common situation of farmers facing diluted wastewater (indirect use), compared to the use of raw sewage or situations where chemical contamination is visually evident. The lack of connection made between symptoms of potential illnesses and exposure are linked to the fact that farmers often explicitly grow crops for the market that they do not consume at home. As such, they do not experience the same illnesses as consumers, who in turn are rarely able to identify the source of their illness, let alone trace it back to a specific farm. To compensate for these educational gaps and circumvent the challenges involved in explaining invisible threats, such as those from pathogens, social marketing strategies or nudging could be employed to stimulate behaviour change (Drechsel, Qadir & Galibourg, 2022), for example by using triggers such as the "yuck factor" to induce hand-washing (Karg & Drechsel, 2011).

10.2.4 Regulatory, institutional and policy factors

Where national water reuse standards are available, they must be supported by wastewater treatment capacities able to generate water suitable for irrigation. As water may still be considerably polluted, even in cases of 90 percent secondary treatment, there is a need for regulatory bodies to monitor the irrigation sector and ensure compliance with risk reduction measures, and enforce water and crop quality testing. In the absence of national regulations, the US standards compiled by the United States Environmental Protection Agency (USEPA, 2012) or the World Health Organization (WHO, 1989) can provide guidance (see Chapter 3). However, in places where the required treatment is not feasible, the enforcement of standards – if actually possible - would result in irrigation being banned in many urban and peri-urban areas, affecting thousands of livelihoods and compromising the urban supply of highly perishable vegetables where cool transport from rural areas is not possible (Drechsel & Keraita, 2014).

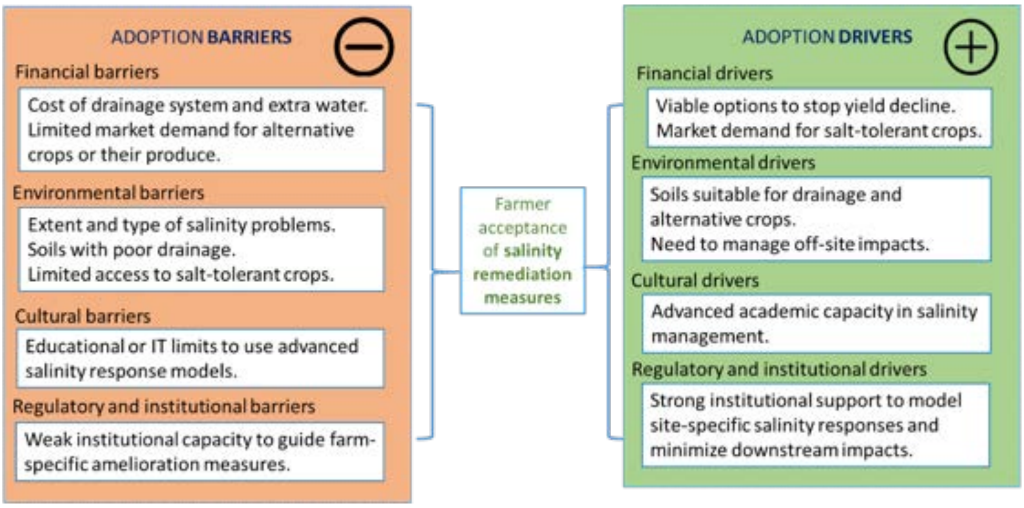
In 2006, WHO, in collaboration with FAO and UNEP, adopted a multi-barrier approach to address the widespread lack of wastewater treatment plants, a situation which makes it impossible to treat water to desirable quality thresholds. Rather than promoting water quality thresholds, the approach taken by WHO (2006) favours the promotion of multiple interventions (barriers) from treatment to farm to fork, which when implemented (ideally in combination) reduce significantly the health risks prior to food consumption (Amoah *et al.*, 2011; Mara *et al.*, 2010). The barrier approach has been adopted since then e.g. by the EU and ISO water reuse guidelines (see chapter 3). These barriers are based on stakeholder actions which necessitate at a minimum behaviour change and require related research into incentive options and institutional support. Training alone is unlikely to facilitate the required adoption of safety practices (Drechsel, Qadir & Galibourg, 2022).

Measures to support behaviour change can include access to credit, labelling, dedicated marketing chains, tax exemptions, the provision of extension services and awards, as well as restrictive regulations where these are enforceable. However, urban farmers often lack any type of land tenure security and can be expelled from their plots from one day to the next. Offering tenure security in such cases can be an appreciated incentive for the adoption of safety measures, like seeking safer groundwater. Labelling of food products in a manner that reveals safe farming practices will support a market response if accompanied by changing consumer risk awareness (Drechsel & Karg, 2013).

10.3. Factors affecting the adoption of salinity mitigation measures

Farmers whose land is affected by salinity have little choice but to adopt mitigation measures in order to avoid financial loss. Farmers are usually well aware of these risks, as salinity (compared e.g. to pathogens) is directly affecting them. However, no single universal mitigation technology is suitable for all soils. Prior to setting up a site-specific soil reclamation plan, it is therefore essential to review the available resources (farmer budget, availability and quality of water, etc.) and the reclamation and yield target objectives to suit the specific needs of the farm. Chapter 5 outline various salinity management options. The most promising interventions usually consist of a specific selection of crops and the leaching of salts out of the root zone. Figure 10.4 shows the typical barriers and drivers for the adoption of salinity mitigation measures, which in contrast to wastewater management have a much stronger off-farm or catchment dimension.

Figure 10.4. Adoption drivers and barriers for the acceptance of salinity mitigation measures



Source: Authors' own elaboration

10.3.1. Financial factors

The economic costs and benefits of reducing salinity can easily be quantified at the farm level. A key requirement is to optimize the management response in accordance with the nexus of biophysical and technical factors for a given size of land. The more factors the model can consider, the higher the probability of optimizing the drainage requirements and the related costs and benefits. However, more complex systems often come at a cost (e.g. software and hardware needs, service charges, education, etc.). This makes free access to advanced salinity management models with (ideally limited) data demands and a user-friendly interface (including for non-specialists) key factors to consider.

10.3.2. Environmental factors

Local site conditions determine to a significant extent the options available to farmers for salinity management. These range from the crops that can be grown to the success of drainage. In contrast to the management of wastewater-related risks, which aim at minimizing the contact between water and crop on farm, the management of salinity has significant off-site implications as the main management tool is to remove salts, with excess irrigation water from the rooting zone discharged off-farm through an appropriate drainage system. These downstream impacts on other irrigated fields, or ecosystems such as aquifers or wetlands, and the environment within each catchment area, have to be monitored and minimized (see below). In this context, payment of farmers for environmental services rendered could be associated to farm management practices based on the environmental benefits achieved.

10.3.3. Cultural factors

Compared to the "invisible" risks of heavy metals or pathogens in wastewater, the need to raise awareness among farmers of soil and water salinity and related amelioration measures is low. The main cultural factor relates to education and access to advanced information to manage salinity, which requires in principal access to laboratory data and computers, and access to advanced soil-water models. Many such models are freely available and come with user-friendly interfaces and a broad range of parameters to minimize data needs (see chapter 5). Alternatively, well-trained extension officers can assist farmers with analysis to calculate optimal leaching requirements and the resulting economic benefits for different crops and soils.

10.3.4 Regulatory, institutional and policy factors

Institutional support to guide farmers in the best salinity management practices, crop choices and drainage requirements for their area is a key requirement in ensuring the most appropriate salinity response. However, salinity management is a catchment task and communities in many salt-affected areas have worked with the government and individual farmers on regional or basin-specific Water Quality and Salinity Management Plans to set salinity targets and to identify and promote sustainable land uses beyond the individual farm plots. This approach enables these communities to protect local groundwater and surface water resources, reinforce environmental values and, where possible, rehabilitate degraded environments. Water Quality and Salinity Management Plans require regulatory support for inter-institutional collaboration towards concerted and cooperative action where no central agency like a basin authority, is in place. Hart *et al.* (2020) share useful lessons from Australia.

10.4 Conclusions

The here presented framework covers key factors which commonly steer context-specific pathways towards improving water quality and the safe use of MQW. It tried to address the very different challenges resulting from water pollution versus salinity, or planned versus unplanned (but already existing) wastewater reuse. In line with Jiménez *et al.* (2019), the framework is emphasizing existing stakeholder capacities and engagement which will be important for participatory processes and the adoption of best practices. Related incentive systems will have to be location-specific and could include certification programs or subsidies financed e.g., through water pricing, or payments for food safety or ecosystem services (UN-Water 2015).

Finally, this discussion of the enabling environment did not dive into situations where water quality is negatively affected by farm management. These situations could be addressed, e.g. through reducing fertilizer subsidies or higher taxation of pesticides to reduce non-point pollution, or stricter monitoring of guideline compliance for point sources, such as the effluent from fish ponds or livestock barns. The capacity to monitor the improvement of water quality, soil salinity, produce safety or the compliance with performance objectives, will be in all here discussed scenarios or cases a quintessential component of the required enabling environment, while the monitoring can be limited to the most critical control points (WHO, 2022).

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Case studies

Case study 1 Ghana

Main information

Project name	Reducing pathogenic health risks where untreated wastewater is used in vegetable production in West Africa
Project website	www.iwmi.cgiar.org/Publications/Success_Stories/PDF/2013/issue_21-making_waves_in_the_field_of_informal_wastewater_use.pdf
Benefits	The project developed, tested and verified with local target groups a set of food safety measures from farm to fork, which FAO and WHO adopted for their guidelines and manuals.
Keywords	Pathogenic risk mitigation, wastewater irrigation, food safety
Duration	2003–2014 (main phase) with follow-up projects under https://wle.cgiar.org/research/themes/rural-urban-linkages
Contact persons	Philip Amoah <philipamoah504@gmail.com>; Pay Drechsel: p.drechsel@cgiar.org

Summary

Where conventional wastewater treatment is lacking or only some of the generated wastewater is treated, water in streams and rivers used for crop irrigation is heavily polluted, and alternative or additional options for health risk reduction are needed (Figure 1). The 2006 edition of the World Health Organization (WHO, FAO) guidelines for the safe use of wastewater, excreta and greywater in agriculture support a multiple-barrier approach here. Safer water fetching and irrigation techniques or on-farm water treatment constitute only some of these barriers and should be complemented by additional barriers and food hygiene protocols in markets and kitchens to address post-harvest contamination. Options were developed and/or tested in Ghana and verified in other African countries. Several options are highly cost-effective, producing a return on investment of 5 to 1 in terms of avoided disability-adjusted life-years (DALY). On-farm and post-harvest options can complement each other but require well-designed adoption strategies that account for limited risk awareness along the food chain. The research was led by the International Water Management Institute (IWMI), Ghana Office in collaboration with WHO and FAO. It complements SDG 6.3.1 which tracks the percentage of wastewater flows that are treated by offering additional or complementary options to safeguard public health.

Figure 1: Urban farmers fetching irrigation water from a wastewater polluted stream in Kumasi, Ghana

Source: IWMI

Project results

Result 1	Quantified log reductions for safety interventions on farms and in markets and kitchens: www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/PUB141/RR141.pdf
Result 2	Cost-effectiveness assessment of on- and off-farm measures: www.tandfonline.com/doi/full/10.1080/02508060.2011.594549 or https://cgspace.cgiar.org/handle/10568/36813 (free access)
Result 3	Analysis of pathways for the adoption of the recommended practices: www.tandfonline.com/doi/full/10.1080/02508060.2011.594684 www.mdpi.com/2073-4441/14/6/864/pdf
Result 4	Videos as training materials for extension staff, farmers and kitchen staff: www.youtube.com/watch?v=Aa4u1_RbIfM www.youtube.com/watch?v=DXHkQE_hFg4&t=6s www.youtube.com/watch?v=oVBDYge868k www.youtube.com/watch?v=s17_35B7SdY
Result 5	Other training materials (including FAO Farmer Field School Manual): www.iwmi.cgiar.org/Publications/Books/PDF/Farmers_Guide-Low_res-Final2.pdf www.fao.org/3/CA1891EN/ca1891en.pdf www.iwmi.cgiar.org/publications/resource-recovery-reuse/series-1/
Result 6	A series of international training events with UN-Water partners: www.youtube.com/watch?v=ArC3lJ2rCo4&t=357s

Lessons learnt

Lesson 1	The low-cost risk mitigation options for farmers, traders (markets) and kitchens (street restaurants, household kitchens) were tested with farmers and other stakeholders, and adjusted and verified in terms of pathogenic risk reduction and low-cost applicability in the local context of West and East Africa. However, lack of follow-up (due to absence of funding) to pilot or implement the options and analyse adoption pathways hindered the promotion of safety practices to trigger lasting behaviour change and uptake.
Lesson 2	The uptake of farm-to-fork risk reduction options requires well-analysed local adoption strategies (awareness creation, incentives, social marketing, punitive measures/regulations, etc.) to support lasting behaviour change. This is important in situations where the target group does not have the educational background to recognize the direct or indirect benefits from safety measures vis-à-vis the discomfort of changing established habits.
Lesson 3	Food safety interventions should prioritize the last point before consumption, as contamination can also take place post-harvest. Such interventions, such as washing salad vegetables with chlorine tablets or potassium permanganate, are cheap, easy to do and will protect the user (and family) or the valued customer of a restaurant. This can provide greater incentives for compliance than burdening a farmer who will neither eat the exotic vegetables nor receive feedback from the actual consumer.

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Useful WHO weblinks:

https://www.who.int/teams/environment-climate-change-and-health/water-sanitation-and-health/sanitation-safety/guidelines-for-safe-use-of-wastewater-greywater-and-excreta

https://www.who.int/teams/environment-climate-change-and-health/water-sanitation-and-health/sanitation-safety/sanitation-safety-planning

Case study 2

Coastal Bangladesh

Main information

Project name	Putting saline agriculture into practice: A case study from Bangladesh
Project website	www.thesaltdoctors.com, www.icco-cooperation.org/en/project/salt-solution
Benefits	After introducing climate-resilient crop varieties and receiving training on specific cultivation techniques, farmers in coastal Bangladesh were able to produce crops in the dry season. During this season, land usually remains fallow due to increasing salinity of soil and water. Adding an extra crop season resulted in a cascade of positive effects associated with the SDGs.
Keywords	Coastal Bangladesh, salinity, saline agriculture, salt-tolerant crops, capacity building, improve resilience, farmers, market opportunities
Duration	2017–2020
Contact persons	Bas Bruning: bas@thesaltdoctors.com Arjen de Vos: arjen@thesaltdoctors.com

Summary

Farmers in coastal Bangladesh suffer from seasonal salinity as seawater intrudes far inland during the dry season, while heavy rains ensure fresh conditions during the wet part of the year (July–September). As part of the Salt Solution Project, salt-tolerant varieties of common crops (cabbage, cauliflower, kohlrabi, carrots, potatoes and beetroots), as well as specific cultivation techniques were introduced and successfully implemented. Adapted farming strategies included, among others, the use of seedlings to take advantage of better conditions for plant establishment and development, crop cultivation on raised beds, improved irrigation management and the use of mulch to ensure a more stable water content in the soil, thus avoiding salinity peaks between irrigation events.

Soil salinity, water quality and crop performance were monitored at 50 different locations distributed over four coastal districts. The pilot farms were held by smallholder farmers who were trained on saline agriculture practices. In most of the cases, their soils were silt loam clay, which did not present sodicity issues. The average soil salinity (ECe) of all 50 locations, ranged from 3.6±2.0 dS/m at the beginning of the season (October, just after the monsoon), to 5.6±3.3 dS/m at the end of the dry season (June). Water quality, as well as its availability, decreased along the season, although the addition of another crop season was possible due to the improvements effected by the above actions.

Through a train-the-trainers approach, the project reached 5 000 farmers within three years. An independent review showed that the introduced saline farming techniques improved many aspects of the farmers' daily lives. With regard to the Sustainable Development Goals (SDGs), the farmers experienced improvement in the following aspects of their livelihoods: household income increased on average by 34 percent, food security rose from 15 percent to 65 percent, vegetable consumption increased from 26 percent to 74 percent, and women's skills in sustainable food production rose from 9 percent to 79 percent (Figure 1). These results show that through proper training and salt tolerant crops, local communities can vastly benefit from an introduction to crop cultivation under saline conditions.

Main information

SDG number	SDG description	Accomplishments after 2 years	Before start of project (%)	2 years after start of project (%)
1	No poverty	**Average household income increased**		34
		Households with more than EUR 100,- monthly increase:		
		- Lead farmers		55
		- Group farmers		4
		Employment increased		
		- Lead farmers		10
		- Group farmers		41
2	Zero hunger	**Food security increased**[a]	15	65
		Use of salt affected fallow land increased[b]	0	76
3	Good health and well being	**Vegetable consumption increased**[c]	26	74
		Households improved dietary diversity	75	100
4	Gender equality	**Skills in sustainable food production of women increased**	9	79
		Access to land for women increased	4	87

[a] Food security is based on household food insecurity access scale- https://www.fao.org/fileadmin/user_upload/eufao-fsi4dm/doc-training/hfias.pdf

[b] During the first part of the dry season (December–February).

[c] Defined as the consumption of a minimum of 150 g/day, during at least 10 months/year.

Lessons learnt

Lesson 1	Farmers are often unaware of the possibilities for adaptation to salinity. They lack access to salt tolerant crop varieties as well as the requisite knowledge and skills needed in the field. By ensuring the availability of input materials (e.g. seeds), providing training and convincing farmers of cost-effective solutions, adaptation to salinity can be achieved in a sustainable and profitable way.
Lesson 2	To convince farmers it is vital to demonstrate the solutions in the field. All farmers are entrepreneurs and the use of new crops/crop varieties, in combination with new cultivation techniques, is often considered a risk. Explaining the crops and techniques, as well as the costs and benefits, is essential for the adoption process, together with training and follow-up.
Lesson 3	Crop cultivation under saline conditions has great potential. Most salt-affected areas are only moderately saline and very suitable for the introduction of more tolerant varieties of conventional crops with high nutritional value and good market potential. The results only two years after the start of the project showed the potential of "saline agriculture", not only for coastal Bangladesh, but for many other-salt affected areas worldwide.

Figure 1: Capacity building targeting skill development of women farmers

Source: https://www.thesaltdoctors.com/

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Murcia, Spain

Main information

Project name	Agricultural water management at district level: Association of Irrigators of Campo de Cartagena (Murcia, Spain)
Project website	www.crcc.es
Benefits	• To address water salinity, four different irrigation water sources are jointly managed and used to irrigate horticultural crops (exterior and greenhouse) and citrus trees. • The project resulted in a positive export-import balance that provides the basis for socio-economic development in the area.
Keywords	Water optimization, reuse, regional planning
Duration	1952 – present day
Contact persons	Mariano Soto Garcia: mariano.soto@crcc.es Pablo del Amor Saavedra: pablo.delamor@crcc.es

Summary

The Murcia Region area is located in southeast Spain and is one of the driest areas in Europe. Historically, water availability, both in terms of quantity and quality, has been one of the most significant constraints on local agriculture. The combination of low rainfall (averaging 300 mm/year) and high evaporation (averaging 1 200 mm/year) set very strict limits on available water resources, resulting in water deficits and under-watering of crops – serious challenges that are further aggravated during periods of drought and water shortages. Conversely, the high quality of soils and mild winter weather create an excellent environment for irrigation underpinning a competitive agricultural economy which is largely export-oriented.

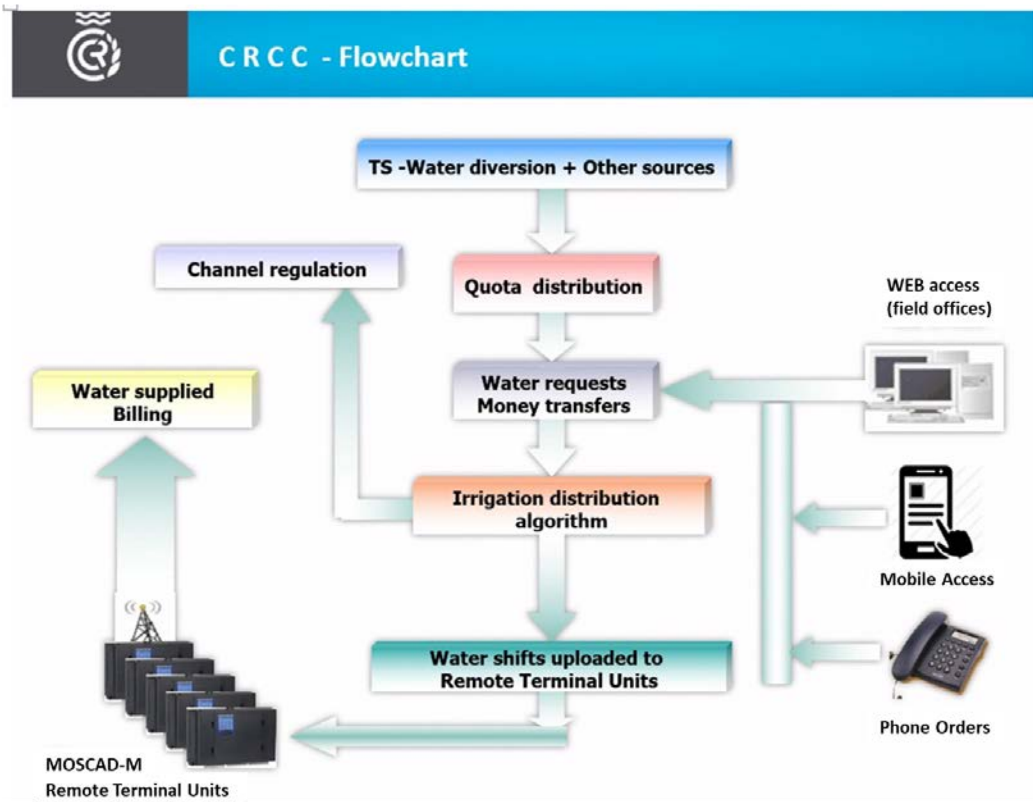
The Campo de Cartagena is an agricultural region located to the south-east of the Murcia Region. It encompasses 1 300 km^2 of which 30 percent is covered by intensive, water-efficient, irrigated agriculture. Irrigation demands are satisfied by water of different origins including surface water external to the system (the Tajo-Segura Water Transfer), partially desalinated groundwater, reclaimed water and, more recently, desalinated seawater. Irrigation draws on a major multilayer aquifer in which the deep aquifers are overexploited and the groundwater level in the shallow aquifer is rising and generating drainage problems. The salinity of the groundwater is high, related in part to seawater intrusion in the shallow aquifer in the 1960s, and more recently to management problems concerning rejected brine from small groundwater desalination plants. In the deep aquifers, salinity is likely associated with age, as the aquifers are confined.

To resolve this problem, local farmers formed irrigation communities. The Irrigation Community of Campo de Cartagena (CRCC) was founded in 1952 and the first irrigation process occurred in 1979. The CRCC (Figure 1) is the largest irrigation community in Europe, due to the integrated water resources management of five different water sources: 122 Hm^3 from the Tajo-Segura water transfer, 4.2 Hm^3 from the Segura River Basin, 4.7 Hm^3 groundwater, 23.6 Hm^3 desalination water and 13.5 Hm^3 reclaimed water from seven wastewater treatment plants (WWTPs)*.

* 1km^3 = 1000 hm^3

Collectively, they have achieved a competitive irrigation water price of EUR 0.36/m^3. At this price, the almost 10 000 members are able to irrigate 41 294 ha of mainly horticultural crops (59 percent) and citrus trees (30 percent) in eight different municipalities. This water conveyance infrastructure has brought progress to eastern Spain and enabled a semi-arid region to be transformed into Europe's vegetable garden. Estimates suggest that CRCC has led to annual wealth generation of about EUR 1 015 million and the creation of 41 500 jobs.

Figure 1: CRCC operational flowchart



Source: Authors' own elaboration

Project results

Result 1	Distribution and storage infrastructure (64 km irrigation channel longitude with a capacity of 300 000 m^3 and a reservoir capacity of 2 090 863 m^3)
Result 2	Irrigation modernization (98 percent surface with drip irrigation)
Result 3	Integrated water resources management using four different water resources

Lessons learnt

Lesson 1	Mixing different types of water with different qualities and different availability was crucial for the sustainability and survival of agriculture in this semi-arid area with great benefits for the environment and society.
Lesson 2	Use the maximum possible amount of reclaimed (waste)water which can be mixed with other water types of different origin and quality.
Lesson 3	Global economic integration and advanced management of the distribution of different sources of water appeared as the best approach to ensuring a sustainable form of agriculture in the study area to meet the uncertainty and potential threats of climate change.

Case study

4 California, USA

Main information

Project name	Integrated Regional or On-farm Drainage Management (IFDM) with a focus on reuse of saline waters for forage production (western San Joaquin Valley of California, USA)
Project website	No dedicated website. Related information can be found at https://water.ca.gov/Programs/All-Programs/Agricultural-Drainage http://stewards.farmland.org/farm/red-rock-ranch http://stewards.farmland.org/farm/andrews-ag
Benefits	Safe disposal of saline agricultural drainage water high in salts, selenium and boron, and reduced discharge of agricultural drainage water into nearby rivers and streams.
Keywords	Saline irrigation, selenium, water reuse
Duration	1998 – present (San Joaquin River Improvement Project (SJRIP) only)
Contact person	Sharon E. Benes: sbenes@csufresno.edu

Summary

Subsurface drainage systems can lower perched water tables to prevent water-logging and the upward migration of salts into the root zone. They also allow for periodic, heavy applications of irrigation water for the purpose of leaching salts below the root zone. In the western San Joaquin Valley of California, disposal of agricultural drainage waters is highly regulated due to the potential for high concentrations of trace elements such as selenium (Se), which can cause toxicity to migratory waterfowl and fish. Reuse of saline drainage water (or other wastewaters high in salts) for forage production can reduce the volume of effluents requiring special management and produce revenue from the harvested hay.

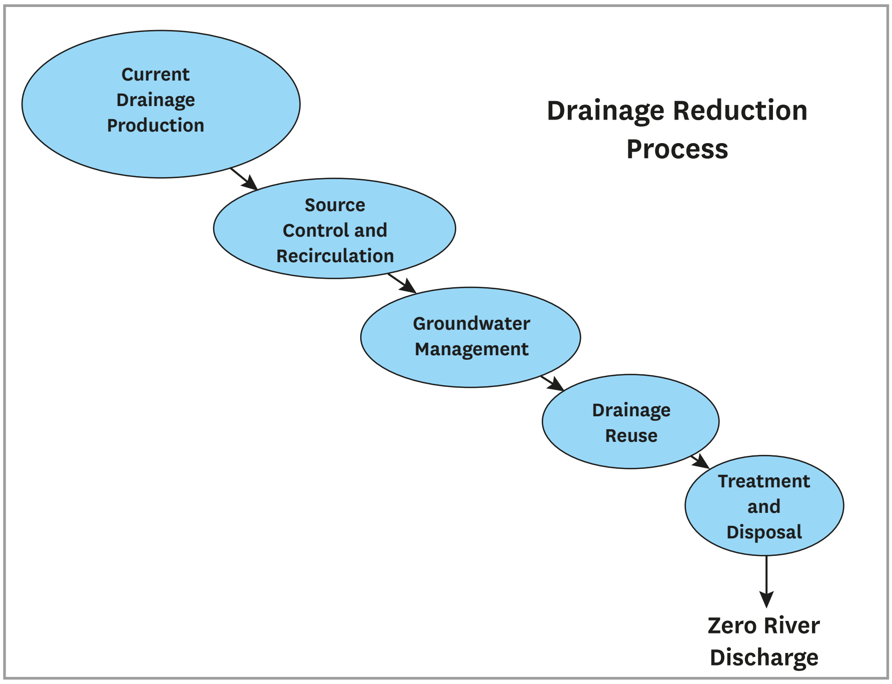
The longest-running saline drainage water reuse site is the San Joaquin River Improvement Project (SJRIP) currently operated by the Grasslands Basin Authority. It was implemented to reduce discharge of drainage waters into the nearby San Joaquin River. The process started in 1998 and by 2012, approximately 29 233 500 cubic metres (m^3) of drainage water was being applied to 2 080 hectares (ha) of lands cropped with "Jose" tall wheatgrass (Thinopyrum ponticum var. "Jose"), Bermudagrass (Cynodon dactylon), alfalfa (Medicago sativa) and pistachios (Pistacia vera) (Figure 1).

Figure 1. "Jose" tall wheatgrass field irrigated with saline subsurface drainage water in the San Joaquin River Improvement Project (SJRIP), February 2013.

Source: Sharon Benes

Currently, the SJRIP comprises 2 428 ha (~30 percent tile-drained) with tall wheatgrass as the primary crop and a small amount of pistachio to provide additional revenue. Saline drainage water reuse forms part of other regional drainage management activities including source control (e.g. conversion to micro-irrigation), groundwater management, and the testing of salt and selenium removal technologies to achieve mandated water quality objectives and, ultimately, zero discharge to the river (Figure 2).

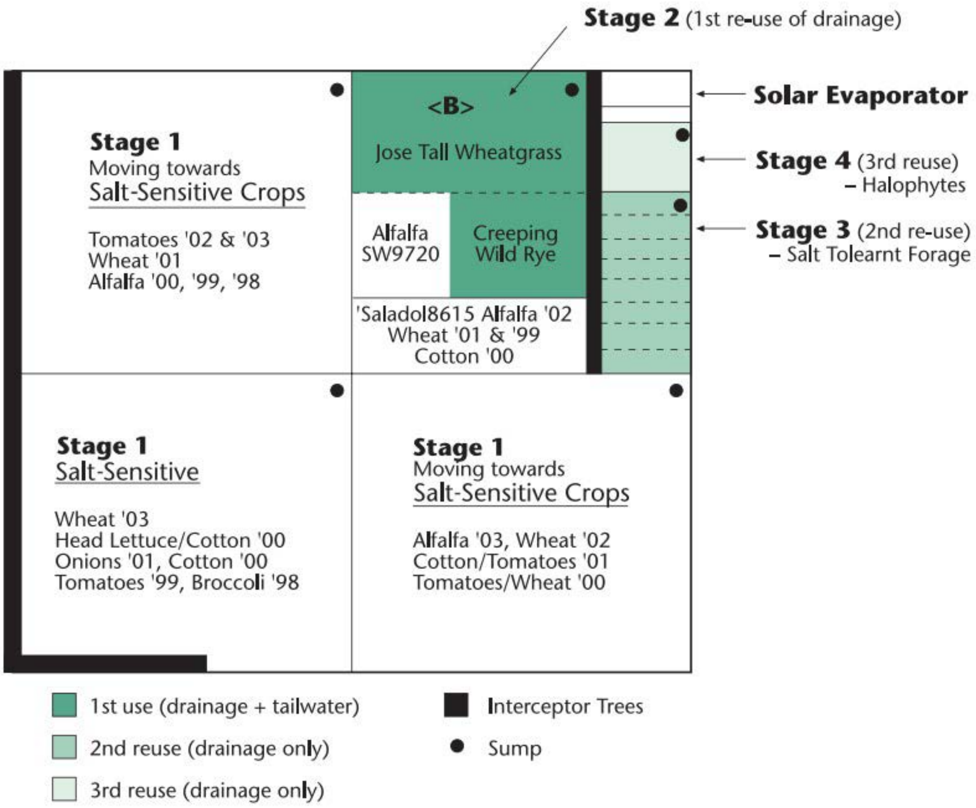
Figure 2. Drainage water reduction components in the Grassland Basin Drainage Area



Source: Linneman, C., Falaschi, A., Oster, J.D., Kaffka, S. & Benes, S.E. 2014. Drainage reuse by grassland area farmers: The road to zero discharge. p. 65-78. Proceedings of the meeting "Groundwater Issues and Water Management: Strategies Addressing the Challenges of Sustainability", US Committee on Irrigation and Drainage (US-CID), Sacramento, CA, 4–7

Two other saline drainage water reuse projects operated on individual farms, referred to as Integrated On-farm Drainage Management (IFDM), are described below. The project that operated at Red Rock Ranch (260 ha, western Fresno County) (Fig. 3) from 1998 to about 2015 involved the sequential reuse of saline drainage water to irrigate progressively more salt-tolerant crops: field crops in the first reuse (e.g. cotton), salt-tolerant forages in the second reuse (e.g. "Jose" tall wheatgrass (Fig. 4), creeping wildrye and Puccinellia) and halophytes in the third reuse (e.g. Salicornia (pickleweed/dwarf glasswort), saltgrass, big saltbush and iodine bush) (Fig. 5). The concentrated drainage effluent was then evaporated to dryness using a 2-ha solar evaporator. Table 1 provides the common and Latin names of the forages and halophytes evaluated.

Figure 3. Sequential reuse of saline drainage water carried out at the 260 ha IDFM project at Red Rock Ranch (western Fresno County, CA), 1998–2015.



Source: Jacobsen, T, Basinal, L., Drake, N.R., Cervinka, V., Buchnoff, K. & Martin, M.A. 2004. Chapter 2: Salt Management using IFDM. In: T. Jacobsen and L. Basinal, eds. A Landowner's manual: Managing agricultural irrigation drainage water. A guide for developing integrated on-farm drainage management systems, pp. 43–56. Fresno, CA, State Water Resources Control Board

Figure 4. "Jose" tall wheatgrass growing in Stage 3 of the IFDM at Red Rock Ranch.

Source: Sharon Benes.

Figure 5. Left: halophyte area, IFDM sequential reuse system operated at Red Rock Ranch: Salicornia (dwarf glasswort, pickleweed) (S. bigelovii) emerging in spring following natural reseeding. Right: mixed halophyte area that formed later in project with saltgrass (D spicata) in foreground (bottom), with Atriplex (A lentiformis) in middle and taller iodine bush shrubs (A. occidentalis) visible in the upper part of the photo.

Sources: Sharon Benes

Table 1. Salt tolerant forages and halophytes evaluated in the IFDM at Red Rock Ranch which persisted and showed promise (additional forages were tested, but did not establish easily or persist).

Salt-tolerant forages	
Common name	**Latin name**
"Jose" Tall Wheatgrass	*Thinopyrum ponticum* var.* "Jose" *(*syn. Agropyron elongatum)*
Creeping (beardless) wildrye	*Leymus triticoides* var.* "Rio" *(*syn. Elymus triticoides)*
Alkali sacaton	*Sporobolus airoides var.* "Solado"
Tall fescue	*Festuca arundinacea var.* "Alta"
Puccinellia	*Puccinellia ciliata*
Alfalfa (salt tolerant vars.)	*Medicago sativa vars.* "Salado", "SW9720"and "SW801S"

Halophytes	
Common name	**Latin name**
Saltgrass	*Distichlis spicata var. stricta*
Pickleweed (saltwort)	*Salicornia bigelovii*
Iodine bush	*Allenrolfea occidentalis*
Atriplex (big saltbush)	*Atriplex lentiformis*
Cordgrass	*Spartina gracilis*

The IFDM at Andrews Ag (485 ha, Kern County) was initiated in the early 2000s and operated for more than ten years. The system was modelled after the IFDM at Red Rock Ranch, but was simplified to include just two reuses of saline drainage water, the first on salt tolerant crops (e.g. cotton) and the second on halophytes. Eventually, the grower began to reclaim the soil in the area of salt-tolerant crops by installing subsurface drainage and he converted to a two-stage IFDM (freshwater irrigated and saline drainage applied to halophytes). An 8-ha solar evaporator was used to concentrate the final effluent.

With both of these IFDM systems, the benefit to the grower was the ability to use subsurface (tile) drainage to reclaim (reduce soil salinity) in the freshwater-irrigated part of the farm and transition from lower value, agronomic crops to higher value, more salt-sensitive vegetables crops such as lettuce, processing tomatoes, bell peppers, melons, carrots, garlic and onion.

Project results

Results 1 to 3 present the outcomes for the SJRIP saline drainage water reuse facility, which manages saline drainage water on a regional scale. Results 4 and 5 relates to saline drainage water reuse projects operated on individual farms, termed as Integrated On-farm Drainage Management (IFDM).

Result 1 (SJRIP)	• Reuse of saline drainage water for forage production reduced agricultural drainage discharge to the San Joaquin River from 71 048 550 m^3 in 1995 to 12 951 m^3 in 2012 – an 82 percent reduction with corresponding reductions in selenium (92 percent), boron (72 percent) and salt loads (84 percent) to the river. • In recent years, drainage volumes to the SJRIP have been lower due to drought and reduced availability of irrigation water. The feasibility of using salt-tolerant crop production to reduce the volume of saline effluents has been demonstrated, as has the long-term sustainability of “Jose” tall wheatgrass production under highly saline conditions (soil salinities of 12.5–19.3 dS/m ECe)
Result 2 (SJRIP)	• Other forages were evaluated for their suitability for saline drainage water reuse systems taking into consideration factors such as salt and boron tolerance, selenium accumulation, forage quality, length of growing season, ease of establishment, competitive ability, and seed or transplant availability. • Overall, “Jose” tall wheatgrass emerged as the top candidate based on its very high salinity and boron tolerance, good forage quality and acceptance in the hay market by local dairy producers.
Result 3 (SJRIP)	• Salinity mapping using the EM-38 electromagnetic induction sensor provided useful maps to assess spatial patterns of soil salinity, laterally and with depth. These maps can be useful to determine adequate levels of leaching to maintain soil salinity at acceptable levels and to identify fields that may no longer be productive due to excess salinity. • EM38 mapping must be done on moist soils with an adequate number of soil samples taken for ground-truthing, and the calibration equation developed must show a good correlation between EC from the sensor and soil salinity (ECe) measured on the ground-truthing samples.

Result 4 (IFDM)	• The Red Rock Ranch IFDM tested several forages in the 2nd reuse area (Stage 3). "Jose" tall wheatgrass proved the most suitable forage for this system due to acceptable hay yield (5.9–8.3 t/ha) in highly saline soils (17.6–19.1 dS/m ECe). Creeping wildrye produced more shoot biomass (10.0–13.8 t/ha), but was grown in less saline fields (12.9 – 13.3 dS/m ECe). Forage quality was lower and the grass proved slightly invasive. Puccinellia has a short growing season, but produced 5.6 t/ha in a single harvest. • All of these grass forages demonstrated a high degree of boron tolerance, as the soils in this part of the reuse project had concentrations of 15–25 mg/kg. • Alfalfa (vars. "Salado" and "801S") produced 16.6 t/ha of shoot biomass under irrigation with less saline drainage water and growing in less saline soils (6.7 dS/m ECe, 7.1 mg/kg B). Forage quality was highest for the alfalfa, but tall wheatgrass had nearly equivalent metabolizable energy (9.3 vs. 9.6 MJ/kg DM).
Result 5 (IFDM)	• Halophytes such as saltgrass, pickleweed (Salicornia) and iodine bush grew well in the IFDM systems at Red Rock Ranch and Andrews Ag, and proved effective in consuming large volumes of saline drainage water through evapotranspiration. • At Red Rock Ranch, soil salinities in the halophyte areas ranged from 17–41 dS/m ECe, with a sodium adsorption ratio (SAR) of 36–43 and boron near 40 mg/kg. At Andrews Ag, soil salinities in the halophyte area were 15–18 dS/m ECe, with a SAR of 23–30 and boron at 22–30 mg/kg.

Lessons learnt

Lesson 1	• A wide range of salt-tolerant forages are available for irrigation with saline waters. Reuse can be an effective management/disposal mechanism to reduce the volume of "problem" waters that cannot be discharged into local waterways and, in some cases, it can produce forage that is marketable and has value. • With saline-sodic waters, care must be taken to minimize the negative impacts on soil structure and water infiltration caused by waters high in sodium. Periodic additions of gypsum or organic matter (incorporated or as a surface mulch) may be needed. However, in the case of perennial forages, the vegetative cover provided by the forage and their fibrous root systems help to maintain soil structure and the infiltrability of the soil.
Lesson 2	• The best forage to choose depends on the chemical composition of the saline water, e.g. whether it is also affected by sodicity (saline-sodic) which can reduce infiltration rates and eventually lead to water-logging in the field. Alfalfa and some other legume forages grow poorly under water-logged soil conditions. If boron concentrations are high in the saline water, then the forage must have an adequate level of boron tolerance. • End use for the forage product is also important. If the forage will be grazed or cut for hay, Mo, NO_3^- and Se should be monitored. High-Se hay can sometimes be beneficial for producers in areas with low-Se soils to prevent Se deficiency in beef and dairy cattle.
Lesson 3	• Halophytes can also be grown under irrigation with saline waters, but in many cases, their forage quality is low, the product market is very limited and, for some, establishment can be difficult. However, where soils are hypersaline (>20 dS/m ECe), perched groundwater is of a very high salinity, or irrigation is performed with waters close to seawater strength salinity, halophytes can be successfully grown and harvested, e.g. Salicornia. • Halophytes can also provide the vegetation needed to lower shallow groundwater levels and prevent soil salinization in areas affected by saline seeps. Each species has its own benefits and drawbacks, but mixed planting, or strips of different species can be undertaken such that if one dies out, another may take its place. Plant establishment can be challenging under hypersaline conditions.

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Case study 5

Kumasi, Ghana; Mirzapur, Bangladesh

Main information

Project name	Safe fish and fish feed production in wastewater-fed treatment ponds (Ghana, Bangladesh)
Project website	https://westafrica.iwmi.cgiar.org/show-projects/?C=1151
Benefits	Safe fish farming options where freshwater is scarce. Low-cost production (no capital costs, limited operational (feed) costs) will keep prices low for the consumer. The treatment plant is well maintained as it benefits from the sale of fish. The income generated removes the need to charge the community any sanitation fees.
Keywords	Aquaculture, health risks mitigation, wastewater stabilization ponds.
Duration	2010 – present (Ghana); 1993- ca. 2013 (Bangladesh)
Contact persons	Philip Amoah: philipamoah504@gmail.com; Pay Drechsel: p.drechsel@cgiar.org

Summary

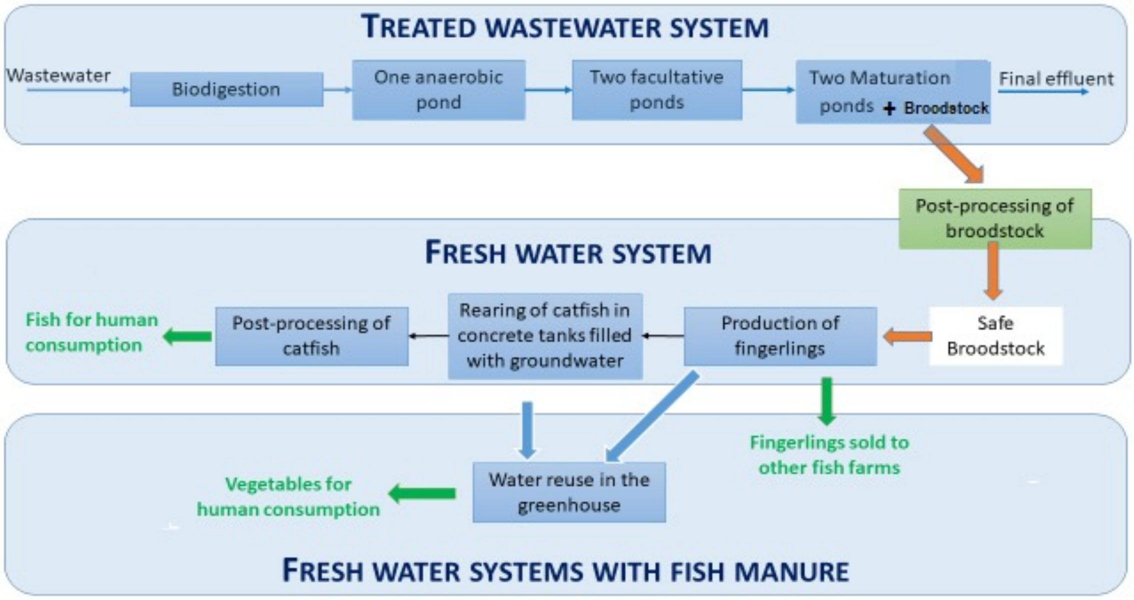
In many regions, the nutritional benefits derived from pond-based aquaculture systems can be substantial. The use of wastewater can add additional environmental and financial benefits where freshwater is scarce and nutrients in the wastewater can be recovered as fish feed instead of contributing to water eutrophication.

The project tested different fish production systems within Waste Stabilization Ponds (WSP) managed by a Public-Private Partnership (PPP) in Ghana, and reviewed other systems in Bangladesh for their safety, value propositions, financial feasibility, socioeconomic and cultural acceptance, and health risk reduction measures. As a result, the project identified three options with high consumer safety and a high probability of viability. The research was supported through different projects between 2010 and 2021, led by the International Water Management Institute (IWMI), Ghana Office, in collaboration with the city of Kumasi, TriMark Aquaculture Centre and, in its first phase, Waste Enterprisers Ltd., who initiated the first PPP, which was later renewed by TriMark.

Project results

In WSPs, catfish are usually reared in the final maturation ponds, with depuration and/or smoking of the harvested fish as measures for risk reduction. An alternative model is to limit the wastewater contact to brood-stock kept in the final pond. Fish eggs are then extracted from the brood-stock for the production of fingerlings in clean water (Figure 1). Another alternative is to produce fish feed only, such as duckweed, in the wastewater, while fish (any type, such as carp) are cultivated in clean water tanks, as in the case study from Bangladesh. All three systems offer benefits to the treatment system operators (cost recovery), fish farmers (no capital costs, limited operational costs) and community (no sanitation fees). Despite the no-risk approach, perceptions have to be closely monitored, especially among consumers.

Figure 1: Process implemented by TriMark in Kumasi, Ghana, in 2020.



Source: Amoah, P., Gebrezgabher, S. & Drechsel, P. 2021. Safe and sustainable business models for water reuse in aquaculture in developing countries. Resource Recovery and Reuse Series No. 20. Colombo, IWMI, WLE.

Result 1	Three business models have been identified which significantly reduce or eliminate risks of wastewater use in aquaculture for fish and fish consumers.
Result 2	All three systems allow wastewater treatment plants to recover their operational costs. The duckweed-based system in Bangladesh (Figure 2) can even recover the capital costs of the pond construction.
Result 3	The project in Kumasi and its PPP won Ghana's Sanitation Challenge Award https://wle.cgiar.org/iwmi%E2%80%99s-wastewater-aquaculture-reuse-project-wins-sanitation-challenge-ghana

Lessons learnt

Lesson 1	Safe wastewater-fed aquaculture is possible and can represent a triple win-win situation from a financial perspective.
Lesson 2	Perceptions of consumers and institutions have to be monitored even where risks are technically eliminated.
Lesson 3	The WSP-based systems can be combined with biogas production and the production of crops irrigated with water from the fishponds (not the treatment plant).

Figure 2: Duckweed-covered plug-flow treatment system in Mirzapur, Bangladesh.

Source: Patwary (2013)

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Case study

6 Western Australia

Main information

Project name	Salinity Mapping in Australia with a focus on remote methods
Project website	National, Victoria, Western Australia, New South Wales
Benefits	Salinization of land is a dynamic process. Continually improving survey and mapping techniques underpins responsive management and cost mitigation at scales varying from farm to river basin.
Keywords	Salinity, mapping, Australia
Duration	1990 to the present
Contact person	Hugh Turral: hugh.turral@gmail.com

Summary

This case is a broad summary of several projects and programmes developed to map natural (primary), irrigated and dryland salinity using a variety of technologies and techniques, across Australia, where the estimated annual cost of salinization amounts to AUD 3.5 billion (Australian National Audit Office, 2004).

Salinity mapping has long been conducted on farmers' fields within irrigated areas as part of whole farm planning. The primary purposes are to improve crop productivity and farm income and the management of recharge to shallow (often hypersaline) groundwater. Electromagnetic survey methods (EM) have been widely used in irrigated areas, where the value of production warrants the costs. Natural salinity has been mapped using a mix of satellite multispectral data, airborne magnetics and in some cases (riparian zones) airborne electromagnetics.

The main objectives in mapping dryland and irrigated salinity are:

- to reduce the impacts of the lost value of production and farm income (AUD 2 billion/year (including acidity), 2019) and land damage (AUD 700 m/year lost capital value, 2018);
- to manage the costs of infrastructure damage (~AUD 250 m/year, 2013);
- to reduce salt accession to streams, wetlands and major river systems in order to minimize ecological disruption to flora and fauna in aquatic and near-stream habitats; and
- to evaluate the results of hundreds of millions of dollars spent on farm and catchment management, community-based salinity management and associated planning.

Project results

Most mapping and management activities and available data refer to the period prior to the end of the Millennium Drought (2010) and include the National Land and Water Audit (NLWA, 1994–2000) and the National Action Plan for Salinity and Water Quality (NAP, 2001–2008).

Result 1
Mapping and costs

- Salinity mapping, especially the dry land variety, is based on the use of visual indicators, especially for vegetation species. This involves the use of numerous protocols and standards as well as the use of satellite imagery.
- Remote mapping relies on contextual information about hydrogeology and geomorphology, including digital elevation models and groundwater behaviour, assessed using low-cost piezometers.
- The costs range widely depending on the scale and methods of data acquisition and data processing employed. The costs of salinity mapping in Australia (ca. 2010) relative to a reference cost of air photo interpretation at AUD 0.1/ha are shown below:

Technique	**Low**	**High**
Air Photo Interpretation (API)	1	
Airborne Magnetic (AM)	8	
Gamma radiometry (airborne)	10	15
Satellite MSS – full analysis	0.05	
Airborne EM (towed) data only	60	150
AEM full product	250	400
LIDAR (light detection and ranging)	50	150
Satellite Radar	50	500
Field techniques		
EM38	25	35
Soil survey	250	450
Commercial Package (2015) *	70	

*(gamma, AM, piezometers, EM38 on the ground – 900 ha dryland farm)

- Drones are also being used for rapid commercial and private application in precision farming, including for salinity mapping.

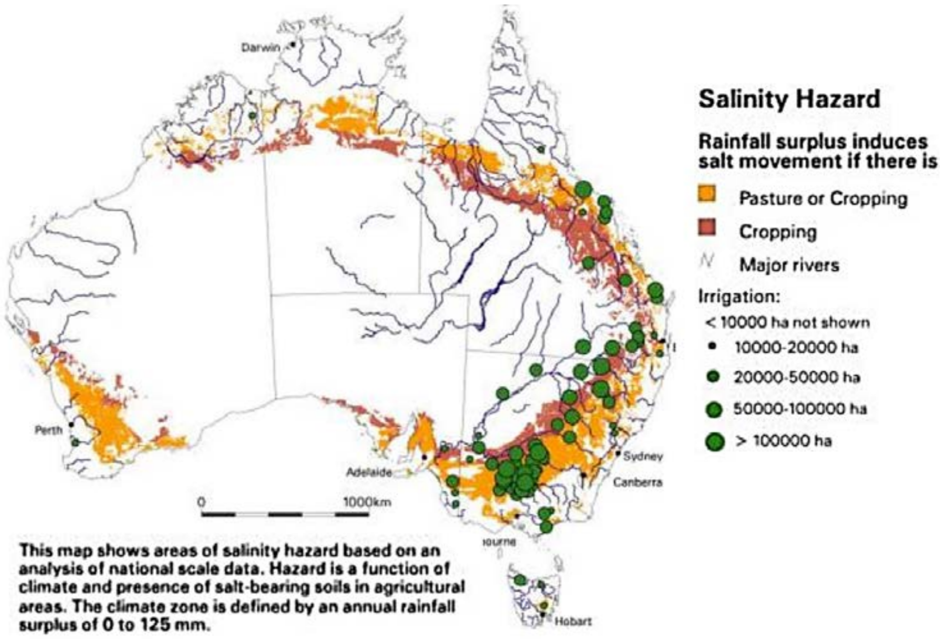
Result 2
The big picture

- Summarized statistics on salinity vary according to the source (state and national assessments), year and definition (areas affected, areas now at risk, areas at risk in the future):

Salinity type	**Total area (ha) (NLWA)**	**Mapped (ha) (NAP)**	**At risk by 2050 (NLWA)**
Natural salt marsh, salt lakes and flats	14 000 000	Most	-
Natural marine salt deposits without groundwater (salt store)	15 000 000	Most	~20%
Irrigated agriculture	~120 000	>90%	>400 000
Dryland agriculture	2 500 000	>20 000 000	17 000 000

- Through improved mapping standards, techniques and investment, the NAP estimates of affected and at-risk areas decreased from the earlier values provided under the NLWA (~2.5 million ha affected) to just below 2 m ha.
- Dryland salinity has come to dominate the policy and statistics on salinity (Figure 1). The Murray–Darling Basin (MDB) salt credit scheme and its successor strategies set limits on the amount of salt each state can export to the River Murray.
- The area where salinity management strategies are applied amounts to 4.45 million ha or 2.26 times more than the area mapped as affected.

Figure 1. Map of irrigated and dryland salinity in Australia

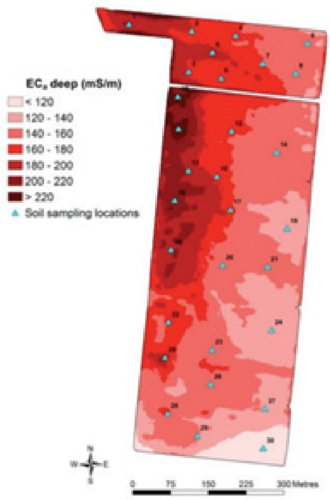


Source: Dent and Veitch (2000)

Result 3 Methods

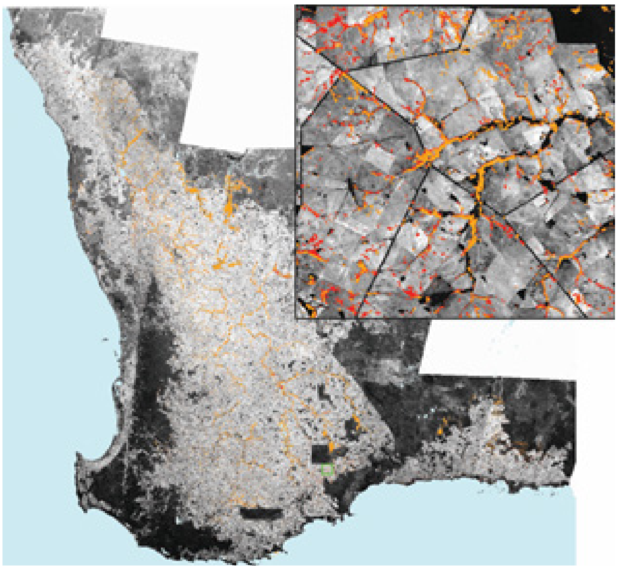
- EM methods provide objective, highly accurate and repeatable surveys and are used on both irrigated and rainfed farms to optimize farm input management (Figure 2).

Figure 2. Farm scale map of electrical conductivity generated from EM38 survey and point sampling



Source: Sugar Research Australia, (2014)

- 18 million ha of land was mapped by CSIRO in Western Australia using multi-spectral satellite (MSS) data. The analysis was considered accurate and identified nearly 4.14 million ha at risk from salinization (example in Figure 3). A follow-up assessment in Victoria (VDPI) concluded that MSS data cannot map soil salinity effectively in areas that have persistent cover of salt-tolerant vegetation (2008).

	Figure 3. Example of dryland salinity mapping in Western Australia: multi-temporal change detection with 10m DEM and ground truth (GPS, vegetation cover, soil condition). The subregion covers 16 x 16 km: areas mapped as salt affected in 1988 are orange, with additional areas in red in 1998.  Source: Furby *et al.* (2010) • Gamma ray spectrometry can assist in mapping soil types and enables salinity modelling. Assessment of deeper underground salt stores requires airborne magnetics (AM) (deep) and possibly airborne electromagnetic (AEM) (near surface) sensors. Both are sufficiently low cost to be use for targeted mapping.

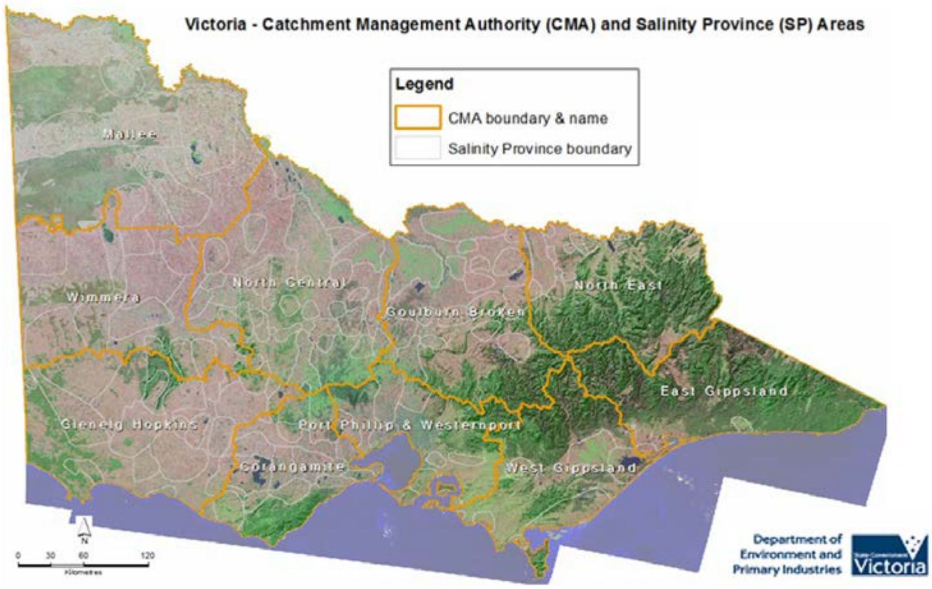
Lessons learnt

Lesson 1 **General**	• Experience in Australia shows that it is unwise to make assumptions about the extent, nature, process and trends in salinity, and that good mapping and monitoring is cost effective and vital to sustainable agriculture and the eco-systems that support it. • Modern methods can be cost effective, but much can be achieved with simple methods, active communities and simple data management. • Cheap GPS and GIS have revolutionized the collection, storage and analysis of geo-spatial data collected thorough specialist and community activities.
Lesson 2 **Cost and benefit**	• Observation by landholders is a cheap and easy way of assessing a site, but the findings are not always correct, and some direct measurements may be needed to confirm the situation. Once further investigation is undertaken, the greater expenses of piezometry and remote survey can be considered. • Salinity survey and mapping can be profitable: in Western Australia, farmers can save AUD 15-30/ha/year in reduced inputs on poor performing parts of the farm, while making an extra AUD 40 to AUD 200/ha/year by increasing inputs on high-performing areas, compared to a one-time commercial cost of AUD 70/ha (see Results 1 above). • Longer term risk in the landscape can be assessed principally through the use of relatively low-cost airborne magnetics. • Tracking hazard development over extensive pastures and broadacre cropping requires continual monitoring of groundwater and climatic conditions with soil and water sampling or EM38 repeat surveys in strategic places at strategic times. All implies costs to the user except the monitoring of climatic conditions. • The comparatively high value of urban buildings, industries and roads justifies greater survey and monitoring costs, providing that the information is used to manage and mitigate those salinity impacts.

Lesson 3 Integration and governance

- The integration of different scales of investigation and governance is important for both local management (paddock and sub-catchment), rural towns and infrastructure, and for long-term monitoring and adaptive management.
- Salinity Provinces remain a fundamental unit of mapping and analysis within a technical administrative framework of Catchment Management Authorities – umbrella organizations for a large range of community land, water and environment groups (Figure 4).

Figure 4. Salinity Provinces in Victoria mapped within Catchment Management Authority boundaries (includes natural, irrigated and dryland agriculture types). The total area under the jurisdiction of Catchment Management Authorities is 22.7 million ha and incorporates 979 soil salinity units which represent 1.09% of the total CMA area.



Source: http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/lwm_salinity-provinces

- The power of modern data collection, mapping and community participation is easily grasped in countries that are less rich than Australia. The relative costs of technologies are constantly changing – often for the better. Improved institutional arrangements, strategic data collection and warehousing bear costs that need careful scrutiny, especially in regard to the benefits they generate.
- Effective action to address salinity can be undertaken by communities and government. Interactive maps on the web represent the public face of science and provide education, communication and digestible information

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Case study 7

Ouardanine, Tunisia

Main information

Project name	Reuse of treated wastewater (TWW) in irrigated agriculture in Ouardanine, Tunisia
Project website	Not yet available
Benefits	The project allowed for crop diversification and landscape improvement and positively impacted the living standards of farmers, who acquired know-how of efficient irrigation and safe wastewater use, and are now acting as promoters of change.
Keywords	Wastewater reuse; good irrigation practices; fruit trees
Duration	1997 – present
Contact persons	Roula Khadra: khadra@iamb.it; Karim Ergaieg: kergaieg@gmail.com
Co-contributors	Olfa Mahjoub, Souad Dekhi, Najet Gharbi

Summary

The area around the town of Ouardanine in central-eastern Tunisia is one of the most successful irrigated areas with treated wastewater (TWW) in the country, dating back to the 1990s. In 1997, the lack of freshwater and the success of a local initiative related to a value-added fruit crop (peach) gradually boosted stakeholder participation and the development of an irrigated public perimeter (50 ha) for a group of 40 farmers. Initially, reuse of TWW supplied through the treatment plant was challenged by quality issues and public acceptance. In response, a farmer-based organization (GDA Agricultural Development Group) was created to promote compliance with regulations and the adoption of good practices in wastewater reuse, and since the early 2000s also the reuse of biosolids. A storage basin and upstream water filters improved water quality and farmers' water access.

Since then, the number of beneficiaries and area covered with irrigation has progressively increased, allowing diversifying crops and expending activities with high economic benefit. Drip irrigation replaced surface irrigation, enhancing water use efficiency and reducing the contact between practitioners, soil, and fruits with water. Each year about 1 000 stakeholders visit the area to learn about the key reasons behind the success of water reuse in Ouardanine, i.e. early farmer participation and the progressive adoption of good practices supported by sound institutional arrangements.

Project results

Improvement of TWW quality for reuse in agriculture	During the first years of operation, the WWTP of Ouardanine failed to provide TWW of a quality sufficient to meet reuse standards and farmers' expectations. Under pressing demand from farmers, further improvements were achieved through the gradual adoption of various post-treatment systems including a battery of filters and a storage basin upstream of the irrigated area. The adopted post-treatment system has improved irrigation water quality in accordance with national regulations.
Evolution of the irrigated area and water reuse	The irrigated area of Ouardanine was established in 1994 and irrigation started effectively in 1997. Currently, the irrigated area stretches over 70 ha and reuses 174 000 m^3 of water per year as compared to the initial 4 000 m^3. More than 50 farmers are part of the established GDA with the majority implementing water reuse for irrigation after observing the results of the first pilot project.

Increased adoption of efficient irrigation systems	Progressive structural improvements supported water quality and availability, and the adoption of modern efficient irrigation systems. Restricted irrigation is fully respected by growing only those crops allowed by the regulations. Farmers adopted various irrigation systems, with some recently adding integrated drippers. The surface irrigation of fruit trees has been replaced by drip irrigation to decrease water consumption and reduce contact between practitioners, soil, fruits and TWW. Cereals and fodder crops are irrigated by the improved surface method.
Diversified cropping pattern with high economic benefits to farmers	Olive trees were the main crops grown. Reuse of TWW resulted in significant modification of the cropping pattern and the socio-economic situation. Currently, cereals, fodder, olive and fruit trees (mostly peaches with some pomegranates, figs and apples) are cultivated. The use of drip irrigation has encouraged some farmers to introduce new crops (mainly industrial varieties authorized by national regulations) such as geranium and cut roses, as well as a nursery to produce roses, olive trees and others.
Referenced Site for know-how transfer and public awareness	Ouardanine is considered a success story for wastewater use in irrigation. The site receives yearly around 1 000 visitors and serves as a demonstration pilot site for biosolid use in agriculture. Good practices for safe reuse in agriculture, quality improvement of TWW, modern irrigation and crop diversification – and especially good governance – are the foundation for this success.

Lessons learnt

Lesson 1	Wastewater reuse in irrigation should meet quality standards and crop requirements. Concerted and co-constructed measures are needed to enhance quality and increase availability, support farmer buy-in and the gradual adoption of modern water-efficient irrigation systems, thereby promoting gradual increase of irrigated areas and the diversification of high value-added crops.
Lesson 2	Financial feasibility, gradual public buy-in and strong leadership are factors important to the success of wastewater reuse, as supporting local value chains further increases farmers' income. The market success of the first or pilot experience and technical support are key factors motivating farmers at the local level.
Lesson 3	Structural improvement coupled with an efficient treatment and filtration process should be accompanied by regular monitoring of TWW quality and the long-term impacts of reuse on soil, crops and groundwater.
Lesson 4	Farmer and stakeholder involvement at all stages of projects from design to operation ensures ownership and sustainability. Sustainable agriculture has been achieved in Ouardanine and the reluctance to irrigate fruits with TWW (referred to as the "yuck factor") progressively resolved by raising awareness, and adopting and enforcing good practices that mitigate negative perceptions of TWW reuse among farmers and consumers. A further planned step is to consider TWW as source of water supply and nutrients, the latter having been neglected to date

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Water quality is of paramount importance for human lives, food production, and nature, and of concern where agricultural pollution, salinization, or lack of adequate wastewater treatment transform water from a resource into a potential hazard. This is in particular the case in many low- and middle-income countries water treatment is not keeping pace with population growth and urbanization resulting in about 30 million hectares of agricultural land, home to over 800 million residents, irrigated with polluted water. In addition to irrigated crop production, animal husbandry and aquaculture may be greatly affected by poor water quality, and can also contribute significantly to water quality degradation.

These challenges prompted the Food and Agriculture Organization of the United Nations (FAO) to publish in 1976 a benchmark publication entitled Water Quality for Agriculture, followed in 1992 by Wastewater Treatment and Use in Agriculture.

Over the ensuing 30 years, water quality challenges have grown resulting in a plethora of new research on water pollution, risk assessments and risk mitigation, as well as various sets of new water reuse guidelines.

Based on this premise, FAO, in partnership with the International Water Management Institute (IWMI), began production of a review of current water quality guidelines, resulting in this one-volume handbook for evaluating the suitability of water for crop irrigation, livestock and fish production. The publication emphasizes good agricultural practices, including risk mitigation measures suitable for the contexts of differently resourced countries and institutions. With a focus on the sustainability of the overall system, it also covers possible downstream impacts of farm-level decisions.

Water Quality in Agriculture: Risks and Risk Mitigation is intended for use by farm and project managers, extension officers, consultants and engineers to evaluate water quality data and identify potential problems and solutions related to water quality, but will also be of value to the scientific research community and students.

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