WFEO / FMOI

World Federation of Engineering Organizations
Standing Technical Committee on Water (CW)

ENGINEERING, WATER AND FOOD NEXUS

FEBRUARY, 2025

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ISBN 978-989-8152-28-2

Acknowledgments

This document results from a collective, disinterested, and generous effort made by the authors and the Standing Technical Committee on Water of the World Federation of Engineering Organizations.

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ENGINEERING, WATER AND FOOD NEXUS

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ORDEM
DOS
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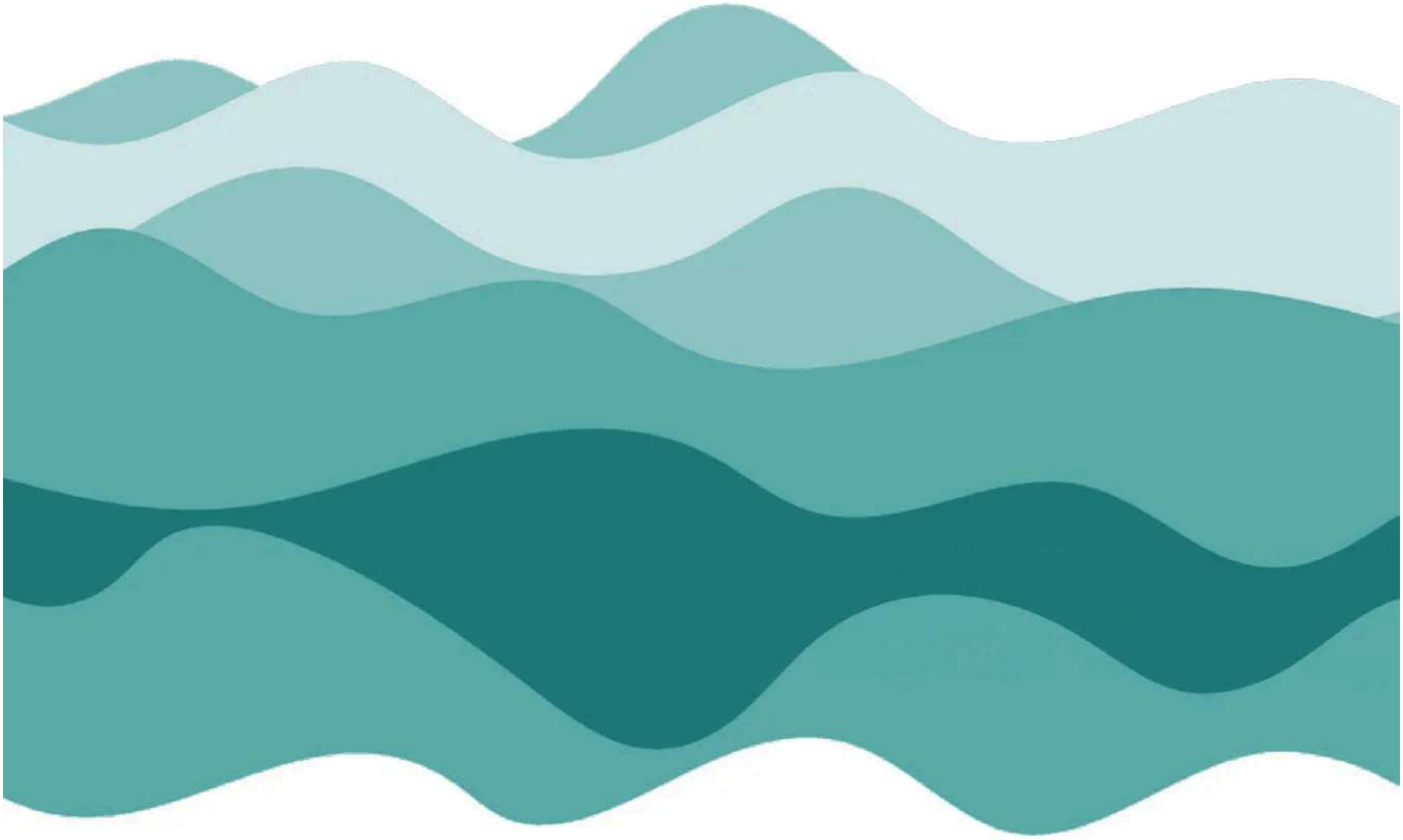

SUMMARY

1. INTRODUCTION

Armando Silva Afonso[1], José Manuel Gonçalves[2]

[1] Retired Full Professor of the University of Aveiro (Portugal), Specialist in Sanitary Engineering in the Portuguese Association of Engineers and current Vice-Chair of the Committee on Water of WFEO. Counsellor Member of the Portuguese Association of Engineers and current President of the Board of the General Assembly of the Centre Region of this Association. He is member of the IWA - International Water Association and member of the Working Group W062 - Water Supply and Drainage for Buildings, from CIB - International Council for Research and Innovation in Building and Construction. As consulting engineer (hydraulics and sanitation), he has developed studies and projects in several countries, such as Portugal, Angola, Guinea, Cape Verde, Mozambique, S. Tomé and Príncipe, Ghana, Senegal and Brazil.

[2] Full Professor of College of Agriculture of the Polytechnic Institute of Coimbra (Portugal). Member of the Portuguese Association of Engineers, Agronomy College. President of the Specialized Commission of Water, Agriculture and Forest of Portuguese Association of Water Resources; Permanent Honorary Member of the Section I Land and Water Engineering of CIGR International Commission of Agricultural and Biosystems Engineering. Researcher of CERNAS - Research Center for Natural Resources, Environment and Society. Experience in irrigation engineering research projects in Europe and Asia during the last 25 years.

The increasing demand for water resources is placing unprecedented pressure on global water systems. This challenge arises from a confluence of factors, including rapid demographic expansion, accelerated economic development, and anticipated climatic changes. These dynamics necessitate the adoption of innovative and effective water resource management strategies. To safeguard the sustainability of this vital resource, it is imperative to promote more efficient and productive water use, with a balanced approach that considers the diverse and competing demands of domestic, industrial, agricultural, environmental, and recreational purposes.

The allocation of water to non-agricultural sectors is steadily rising, further intensifying the pressure on existing water supplies. Climate variability exacerbates this issue, altering the volume and distribution of water storage and fluxes over time and space. This has resulted in a notable reduction in water availability for irrigated agriculture, compromising food production and the conservation of natural resources. Such constraints disproportionately affect smallholder and subsistence farmers, often leading to adverse social, economic, and environmental consequences. Given these dynamics, there is an urgent need to assess the value of water use in agriculture to fully understand the global impact of these changes.

Moreover, identifying and implementing technical solutions for agronomic and irrigation practices is essential to adapting to climate change and promoting sustainable development. Engineering plays a crucial role in this adaptation process, driving scientific and technical innovation that equips the water sector with cutting-edge resources, including advancements in infrastructure, monitoring, and management systems. These innovations have already yielded significant successes. New technological tools, such as advanced monitoring and sensing systems, continue to offer promising solutions. These tools push for more ambitious modernisation, ultimately improving the quality of water distribution, supply systems, and environmental sustainability while minimising ecological impacts.

The Engineering-Water-Food nexus concept underscores the interconnectedness and interdependence of natural resource use — specifically soil, water, and energy — and global food security. This is especially relevant in vulnerable regions where food security is a pressing issue. As humanity grapples with the challenges posed by climate change and population growth, a comprehensive understanding of the nexus is vital for advancing sustainable development.

This book focuses on one critical link in the nexus: the relationship between water and food. It addresses the primary challenges associated with water use in agricultural food production, with the goal of highlighting, analysing, and projecting the contributions of engineering in addressing these issues. Various potential solutions to mitigate water scarcity and associated environmental problems are explored. The analysis presented here is necessarily multidisciplinary, incorporating insights from diverse technical and scientific fields alongside engineering. This approach reflects our belief that interdisciplinary collaboration is essential to devising the new strategies and solutions that the future will demand in this area.

The editors extend their deepest gratitude to all contributing authors and collaborators whose expertise has enriched this publication. We hope that this book serves as a valuable contribution to the ongoing discourse on water, agriculture, and engineering, fostering new synergies and driving the development of innovative engineering solutions that will benefit "our common future."

2. CLIMATE CHANGE AND FOOD SECURITY

Rogerio Bonifácio[1], Valentin Pesendorfer[2], Lorenzo Bosi[3], Muhamad Fajrin[4]

[1] Senior Climate and Earth Observation Adviser, leading a team of 30 specialized staff that make up the Geospatial and Remote Sensing Unit at World Food Program - HQ in Rome. He is an expert in applications of remote sensing and climate data to early warning, seasonal monitoring and food security. He holds a PhD in Meteorology, and joined the WFP operations in Sudan in 2005.

[2] Lead Data Engineer with the Geospatial and Remote Sensing Unit at WFP-HQ in Rome. He leads the development of the cloud computing infra-structure for climate and earth observation data at WFP. He holds a degree in Environment and Bio-Resources Management from the University of Natural Resources and Life Sciences (BOKU, Vienna) and joined WFP-HQ in 2016

[3] Asset Creation and Livelihoods Team Leader. Lorenzo is a programme manager and policy advisor in the field of food security with more than 14 years of experience in WFP in natural resource management and resilience building in the context of climate change. Lorenzo holds a MSc degree in Water Resource Management from Oxford University and a BA and MA in Political Science.

[4] Community Infrastructure Engineer at WFP. Based at WFP headquarters in Rome, Italy, he is part of a global workforce of over 200 engineers and technicians working in infrastructure projects worldwide, with the shared goal of building a more sustainable and resilient future towards zero hunger. Muhamad currently provides technical support for engineering projects and community projects related to the creation of assets such as bridges, dams, roads or irrigation systems.

2.1. Global Food Security Situation

The global food security situation is evaluated using a variety of complementary metrics, each capturing different aspects of the issue. However, these metrics reveal a common trend: global food insecurity has worsened over the past decade. The decline in the number of people facing hunger ended in 2014, and since 2017, the trend has reversed.

The global situation is assessed by the annual State of Food Security and Nutrition in the World (SOFI) report (https://openknowledge.fao.org/items/2241e4d7-dbcb-46e9-ab05-70db6050ccf9). This report provides estimates of hunger at global, regional, and country levels, and tracks progress towards ending hunger (SDG Target 2.1) and all forms of malnutrition (SDG Target 2.2). According to the latest SOFI report, global hunger remained relatively unchanged from 2021 to 2022 but is still significantly higher than pre-COVID-19 levels. In 2022, approximately 735 million people faced hunger, 122 million more than in 2019.

There are significant geographical variations in hunger trends. Some progress in Asia and Latin America contrasts with worsening conditions in Western Asia, the Caribbean, and all subregions of Africa, where 20% of the population faces hunger, compared to 6.5% to 8.5% in other regions. Globally, women and rural populations are disproportionately affected.

Global Hunger projections for 2030 indicate that nearly 600 million people will face hunger, 119 million more than expected without the pandemic and the war in Ukraine. Improvements are expected primarily in Asia, while Africa is predicted to experience significant worsening.

The increase in global hunger is driven by several factors: rising conflict situations, climate variability and extremes, economic slowdowns, and food price increases. These drivers interact in complex ways, often exacerbated by climate change driven instability in global weather patterns.

ASSESSING FOOD SECURITY

Global Hunger: The Prevalence (or number) of Undernourishment (PoU/NoU) is used by FAO to estimate the extent of hunger in the world (Global Hunger). Undernourishment is a statistical methodology using data readily available for most countries in the world, that measures chronic hunger defined as the long-term or persistent inability to meet minimum dietary energy requirements. PoU measures how many people do not have regular access to enough calories, or dietary energy, for an active and healthy life and is included in Sustainable Development indicator framework as SDG Indicator 2.1.1, to monitor progress towards zero hunger. This undernourishment measure does not tell us anything about what specific individuals are undernourished. (https://www.fao.org/interactive/state-of-food-security-nutrition/en/).

A person is food insecure when they lack regular access to enough safe and nutritious food for normal growth and development and an active and healthy life. This may be due to unavailability of food and/or lack of resources to obtain food. Food security is characterized by its four dimensions: Availability (whether food is available or not), Access (whether food is economically accessible), Utilization (uptake of nutrients) and Stability (how predictable access to food is).

Two types of food insecurity are generally considered: Acute and chronic food insecurity. Acute food insecurity is any manifestation of food deprivation that threatens lives or livelihoods regardless of the causes, context or duration. Chronic food insecurity persists over time, largely due to structural causes. The tool most commonly used to assess food insecurity is the Integrated Food Security Phase Classification (known as IPC)

IPC (https://www.ipcinfo.org/) is a common global scale for classifying the severity and magnitude of food insecurity and malnutrition. It provides decision-makers with a rigorous, evidence- and consensus-based analysis of food insecurity and acute malnutrition situations. It mostly informs emergency responses but also medium- and long-term policy and programming. Increasingly, the IPC is the international standard for classifying food insecurity and malnutrition.

The IPC Acute Food Insecurity scale categorizes acute food insecurity into five phases of severity, ranging from Phase 1, corresponding to No/Minimal acute food insecurity, to Phase 5, corresponding to Catastrophe/Famine. Each of these phases has important and distinct implications for where and how best to intervene.

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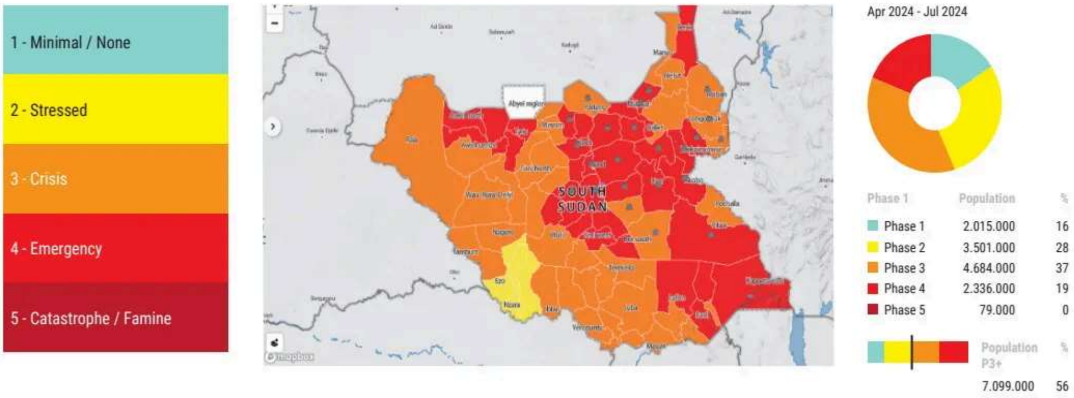
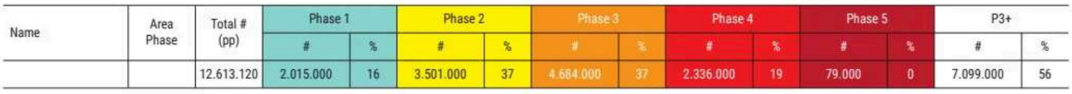
5 SEVERITY PHASES





Name	Area Phase	Total # (pp)	Phase 1		Phase 2		Phase 3		Phase 4		Phase 5		P3+	
			#	%	#	%	#	%	#	%	#	%	#	%
		12.613.120	2.015.000	16	3.501.000	37	4.684.000	37	2.336.000	19	79.000	0	7.099.000	56

https://www.ipcinfo.org/fileadmin/user_upload/ipcinfo/manual/IPC_Technical_Manual_3_Final.pdf

IPC analysis carried out by its stakeholders (Government, UN Agencies, NGOs) provide estimates of the proportion of the population in each of its five phases and projections for the near term.

For operational purposes, humanitarian agencies estimate levels of acute food insecurity for countries using (mostly) IPC and information from other related types of assessments. The most well-known assessments include the Global Report on Food Crises, GRFC (www.fsinplatform.org/grfc2024) and the WFP-FAO joint Hunger Hotspots Report (https://www.wfp.org/publications/hunger-hotspots-fao-wfp-early-warnings-acute-food-insecurity-june-october-2024-outlook).

The Global Report on Food Crises focuses on acute food insecurity in countries experiencing food crises and defines a food crisis as a situation where acute food insecurity requires urgent action and exceeds the response capacity. It mostly uses IPC derived information complemented by other types of assessments and information from household surveys. The latest report covers 59 countries (for which data is available) out of the 73 countries in a food crisis situation.

The GRFC reports that nearly 282 million people in 59 countries and territories experienced high levels of acute food insecurity in 2023 - a worldwide increase of 24 million from the previous year. These numbers correspond to about 22 percent of the population assessed, a proportion that has significantly increased from the pre-COVID-19 levels.

Conflict and insecurity, economic shocks and weather extremes are the primary driver in broadly equal proportions of the countries analyzed, but conflict/insecurity contributes with about as many people affected as the other two drivers put together – in any case these drivers are interlinked and mutually reinforcing. Acute food insecurity is rarely driven by a single shock or hazard, but rather by the interaction between shocks and underlying poverty, structural weaknesses, and other vulnerability factors.

The Hunger Hotspots Report by WFP and FAO assesses the food security outlook for the next six months. The report identifies 18 hunger "hotspots" in a total of 21 countries or territories where it is expects a significant deterioration of already high levels of acute food insecurity. In the latest issue, the hunger hotspots include countries with Famine or Risk of Famine, or with populations already in (or deteriorating towards) Catastrophe (IPC Phase 5) during the outlook period. Mali, Palestine, South Sudan, Sudan and Haiti are the areas of highest concern. The selection of hot spots is made by expert consensus based on IPC data, economic and political outlooks and development of major climate drivers such as El Niño.

Armed conflict remains the primary causes of acute food insecurity across the most important hunger hotspots, as it leads to widespread displacement, destruction of food systems and reduced humanitarian access. Unfavorable economic conditions (low growth, high debt burden, food price inflation) and climate extremes such as the catastrophic drought in Southern Africa (leading to disaster declarations in Zambia, Zimbabwe and Malawi) compound a worsening situation.

World Food Programme Operational Estimates: Useful as these reports are, an operational agency such as the World Food Programme needs numbers of people in acute food insecurity in order to plan its operations, advocate for countries in crises and ensure global coverage of needs – these figures need to offer complete coverage of the countries where WFP has a presence and are as complete, recent and reliable as possible. To arrive at this complete overview, WFP complements IPC or equivalent information and fills information gaps with recourse to other recognized assessments of acute food insecurity.

WFP estimates that in 2024, 309 million people will be acutely food insecure across 72 countries where WFP has an operational presence and where data is available (https:// docs.wfp.org/api/ documents/WFP-0000156605/download/). The WFP number of acutely food insecure is based on peak numbers of the current year, if available, otherwise the latest peak available is used as an estimation. Due to methodological differences and different coverage in terms of countries and populations (WFP includes refugees and internally displaced) these figures are different and not directly comparable with those of the GRFC (https://docs.wfp.org/ api/documents/WFP-0000156604/download/).

The GRFC reports on the past year or first half of the current year and aims at providing yearly comparable and consensus-based figures of global acute food insecurity. WFP figures are forward looking (for the current year), updated three times a year and used for operational planning and decision-making, through WFP's Global Operational Response Plan (GORP, https://www.wfp.org/publications/wfp-global-operational-response-plan).

2.2. Climate Change as a Driver of Food Insecurity

Changes in temperature and rainfall patterns can significantly impact agriculture by altering growing seasons, reducing crop yields, and affecting the viability of certain crops. Additionally, these changes can lead to more frequent droughts and floods. The increased frequency and severity of extreme weather events, such as tropical storms, can disrupt agricultural production, infrastructure, and supply chains.

Climate change-induced alterations in snow and glacier patterns can have serious consequences for fragile states like Afghanistan, which rely heavily on glacier and snowpack melt for irrigation. Regions dependent on cross-border water resources, such as Iraq's reliance on the Tigris and Euphrates rivers, will face compounded disruptions from excessive water use and long-term decreases in seasonal rainfall.

Warmer temperatures can lead to the spread of pests and diseases that affect crops and livestock. Increased temperatures and altered precipitation contribute to soil erosion, desertification, and loss of arable land, reducing the capacity for food production.

An often-overlooked impact of climate change is its effect on global supply chains. For example, severe drought in Central America during the recent El Niño event disrupted shipping traffic through the Panama Canal, highlighting the potential for significant disruptions due to climate variability.

The impacts of climate change rarely act in isolation; they interact with other drivers of food insecurity, leading to unforeseen and sometimes amplified consequences. Intense droughts in Syria in the late 2000s led to significant migration of destitute farmers to urban centers, contributing to the civil unrest that ultimately would lead to the Syrian civil war.

Impacts on food production and supply chains inevitably influence prices, and the resulting economic impacts can drive political and social unrest, potentially leading to significant geopolitical changes and large-scale conflict, as seen with the Arab Spring and the global food price crisis of the late 2000s. Geopolitical events unrelated to climate change, such as the Ukraine-Russia war, can have widespread ramifications on global food production and interact with climate impacts like large-scale droughts driven by climate variability. This illustrates how the three major drivers of food insecurity—climate, conflict, and economic crisis—can interact in complex and unpredictable ways.

2.3. Addressing the Challenges

Climate change is a complex driver of food insecurity, affecting agricultural productivity, supply chains, economic stability, and nutrition. Addressing these challenges requires comprehensive strategies that include climate adaptation and mitigation, investment in resilient agricultural practices, and policies to support vulnerable populations. Collaborative efforts between international organizations, governments, and local communities are essential to build resilient food systems capable of withstanding the impacts of climate change.

Humanitarian agencies play a crucial role in addressing these challenges. The World Food Program (WFP) works across two main axes reflected in its mission statement: "Saving Lives / Changing Lives."

Saving lives by providing emergency relief during crises for millions of people worldwide. WFP's huge logistic capacity ensures delivery of emergency assistance, relief and rehabilitation, development aid and special operations to people affected by conflict and natural hazards. Two thirds of WFP work is in conflict-affected countries, where people are three times more likely to be undernourished.

Changing lives by increasing the resilience of people and communities, fostering adaptation to climate change, promoting good nutrition, and improving food systems to enable a more prosperous future for millions. In 2023, WFP transferred food to over 100 million people and disbursed around US$2.8 billion in cash-based transfers to an estimated 51.6 million people – strengthening food and nutrition security and sustaining local economies around the world. WFP defines resilience as "the capacity of individuals, households, communities, institutions, and systems to manage shocks and stressors without compromising long-term development prospects". 'Managing' refers to the capacity to prepare for, anticipate, absorb, recover, adapt, and transform in the face of shocks and stressors.

WFP has made great investments in resilience interventions, a range of strategies designed to enhance the capacity of vulnerable communities to withstand, adapt to, and recover from climate-related shocks and stresses. While resilience is not achieved through a single operation, but rather through an integrated approach, in many contexts where WFP operates, Asset Creation and Livelihoods interventions represent the foundation of resilience building activities. These interventions (known as Asset Creation and Livelihoods programs) reduce vulnerability, enhance food security, promote sustainable livelihoods, build climate-resilient infrastructures, and strengthen community cohesion and governance.

In both emergency and longer term development contexts, these programs include promoting improved access and management of natural resources, through soil and water conservation, ecosystem restoration, agroforestry, conservation agriculture, and the use of climate-smart technologies; building improved irrigation systems and flood defenses, as well as building or rehabilitating small infrastructure such as roads and bridges, while involving communities in decision-making for effective community-based natural resource management and strong local governance. Therefore, asset creation and livelihoods interventions contribute to the stability, sustainability, and efficiency of food systems, ultimately ensuring food security for vulnerable communities in the face of a changing climate.

The dual focus of saving and changing lives across an organization operating in numerous countries and assisting millions of people creates significant demand for engineering services across various disciplines, including:

I. Computer science and data engineering to provide climate and natural hazard related evidence to properly inform and evaluate WFP's emergency response and programme interventions.

II. Major infra-structural works to enable WFP's emergency and programmatic assistance to be deployed in the countries where it operates.

III. Engineering for resilience interventions that support restoration of physical elements of food systems and the natural resource base of local ecosystems.

Integrating these engineering services, WFP can contribute to effectively address the multifaceted challenges posed by climate change and food insecurity.

2.4. Early Warning and Climate Monitoring Systems

The World Food Program has a longstanding capacity for generating insights from satellite-borne Earth Observation (EO) data. This capability is vital for both immediate emergency response and long-term programmatic planning. From 2014, WFP initiated the systematic regular monitoring of growing season conditions over its areas of intervention based on global Earth Observation data sets, marking the beginning of a systematic usage of EO data for humanitarian purposes. This monitoring aimed at the early identification of climate hazard situations that might lead to food security challenges, enabling more timely interventions.

Exponential Growth in Data Requirements

Over recent years, the requirements for data storage and processing capacity at WFP have increased exponentially. This surge is driven by several factors:

Increased availability of EO data: The volume of freely available EO data has grown significantly, with many satellite sensors providing data at increasingly comprehensive coverage and higher frequency updates.

Enhanced spatial resolution: Improvements in sensor technology have resulted in finer spatial resolution, providing more detailed imagery. The data size increases inversely proportional to the square of the spatial resolution, meaning that halving the spatial resolution leads to a fourfold increase in data size.

Greater spectral resolution: Optical EO sensors capture multiple spectral bands (i.e., separate observations across the electromagnetic spectrum), enhancing the ability to analyze various aspects of the Earth's surface and atmosphere. Modern sensors have an increasing number of spectral bands, which directly increases data size.

To address these growing data challenges, WFP strategically invested in the development of a central, cloud-based data management and processing system known as the Humanitarian Data Cube (HDC). This innovative platform allows WFP to efficiently store, process, and serve vast amounts of EO data.

HDC is built on scalable cloud resources, utilizing cloud-native file formats and cutting-edge geospatial technology to ensure optimal performance and compatibility with modern data analysis tools. By leveraging both vertical scaling (increasing the size of individual processing nodes) and horizontal scaling (increasing the number of processing nodes), HDC can process and provide EO data at scale, at a global scale.

In addition, HDC leverages serverless cloud services and advanced autoscaling where possible, allowing used resources to scale down to zero in times of no demand. Along with the reduced burden of maintenance the serverless model provides, the cloud provider's pay-on-demand pricing model and the use of discounted spare compute capacity allows WFP to efficiently maintain the operation of the Humanitarian Data Cube.

Impact on Emergency Response and Programmatic Interventions

The integration of advanced data engineering solutions has significantly enhanced WFP's ability to respond to emergencies and implement effective programs. For instance, during natural disasters, real-time EO data processed through the Humanitarian Data Cube enables WFP to assess the extent of damage, identify affected areas, and allocate resources more efficiently. In conflict-affected regions, EO data helps monitor displacement patterns and plan humanitarian interventions accordingly.

Moreover, the insights derived from EO data support long-term resilience-building efforts. By understanding climatic patterns and environmental changes, WFP can design programs that promote sustainable agricultural practices, mitigate the impact of climate change, and improve food systems' overall resilience.

Software and data engineering are now an indispensable component of and serve both dimensions of WFP's mission. The strategic investment in tools like the Humanitarian Data Cube enables WFP to respond to increasing requirements in analytical requirements (Figure 1).

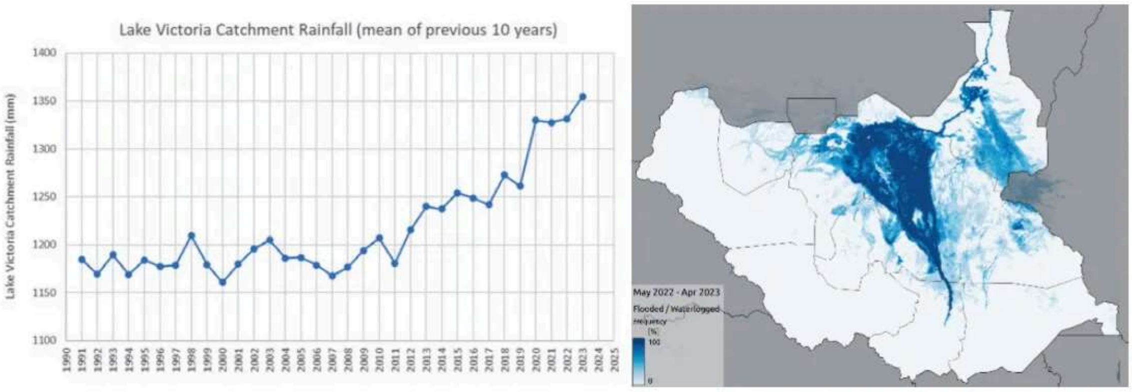


Figure 1: A multi-year emergency in South Sudan – HDC long term data records are processed to provide clear evidence of the increase in Lake Victoria catchment rainfall. Chart on the left shows running 10-year mean rainfall (each point is the mean rainfall of the past 10 years). Seven of the 10 wettest years on record (since 1981) occurred in the past ten years. This increase in catchment rainfall led to Lake Victoria reaching it highest levels since the late XIX century. The resulting record outflows have led to a massive expansion of the Sudd wetlands in South Sudan. The map on the right shows the extent of the flooding in 2022-23 across the country – darker shades represent increasingly permanent presence of water in this period. This is the record extent so far, but is expected to be broken in late 2024, given the continued rise in Lake Victoria levels. The flooded extent has been mapped with recourse to long time series of MODIS satellite thermal infra-red data using in-house analytical and algorithm development expertise. The flood mapping products inform the activities of the humanitarian and government agencies on the ground and allow preliminary estimates of affected population and loss of livelihood resources.

5. Engineering in the humanitarian sphere: the case of the World Food Program

The World Food Program's Engineering team is part of the Management Services Division and is composed of over 200 in-house engineers and technicians across more than 40 countries, supported by a team of specialist engineering professionals at its headquarters in Rome. This team provides critical support and efficient responses for both emergency operations and long-term development programs, represented in WFP's mission of "Saving Lives and Changing Lives." Additionally, WFP offers engineering services to the broader humanitarian and development community, including UN agencies, governments, and NGOs.

WFP Engineering delivers a comprehensive range of professional services encompassing various phases of project management. These services are executed either by the in-house engineering team or by global and regional consultancy firms under long-term agreements with WFP (Figure 1).

Large scale infra-structure for humanitarian assistance

One of the key factors of food insecurity is access, which includes both economic access (the ability to buy food) and physical access (the ability to reach food). Extreme food insecurity typically occurs when low food production coincides with populations being isolated or unable to access markets. WFP Engineering plays a significant role in protecting, restoring, creating, and enhancing basic infrastructure essential for the efficient storage and delivery of humanitarian assistance and reducing the isolation of food-insecure communities. Key activities include:

- Bridge construction and repair: Deployment of steel bridges in remote areas such as Ethiopia or South Sudan.

- Roads and culverts: In South Sudan, WFP has rehabilitated nearly 4000Km of trunk roads, decreasing the need for costly air operations and making food delivery much more affordable.

- Airstrips: Construction and rehabilitation of aircraft landing strips to support the United Nations Humanitarian Air Service (UNHAS). UNHAS runs regular scheduled flights between key locations in countries where existing air travel is deemed too irregular or unsafe, such as South Sudan, Afghanistan, etc., to ensure UN staff and assistance can safely reach communities.

- Warehouses and humanitarian response depots: Construction of strategically located facilities to enable the efficient storage and rapid deployment of food and non-food assistance to disaster-affected areas.

- Community infra-structure: Building and rehabilitating school kitchens, food processing units, irrigation canals, health emergency facilities, and community markets, among others.

- Clean energy solutions: Installation of solar power systems and clean cooking solutions in different kinds of infrastructure such as logistics centers, guesthouses, school kitchens or irrigation schemes.

WFP Engineering significantly enhances the efficiency and effectiveness of humanitarian assistance, ensuring that food reaches the most vulnerable populations. (Figure 2).

Figure 2: Kuajok Bridge in South Sudan built by WFP Engineering. This bridge proved essential in the transport and delivery of humanitarian assistance during the multi-year flooding event affecting the country. Photo: WFP/Country Office Engineering team

Engineering for resilience interventions

WFP Engineering plays a crucial role in Asset Creation and Livelihoods (ACL) programs by providing technical expertise and guidance to support the design and implementation of community-built asset projects. These initiatives contribute to ecosystem rehabilitation by combining food assistance with technical capacity to build or rehabilitate community or household assets, restore degraded land, and improve natural resource management. ACL activities offer numerous benefits, including improved access to food and better nutrition, reduced risks, increased resilience to shocks, strengthened dialogue and cooperation between communities, and promotion of gender equality and women's empowerment. WFP engineering teams ensure that these assets meet quality, safety, and sustainability standards, enhancing their long-term impact. Asset Creation and Livelihoods (ACL) programmes make a significant contribution to more resilient food systems by increasing productive potential, restoring physical elements of the food system, supporting local food production and value chains, and managing climate risks and other drivers of vulnerability.

Infra-structure: Rehabilitating market infrastructure and access roads to connect remote agricultural areas to markets significantly reduces transportation time and costs for farmers. These interventions enhance the resilience of the food system by ensuring that production can be efficiently transported and marketed.

Water management systems: WFP engineers design and implement various water management systems, including irrigation schemes, water harvesting structures, and flood control measures. Structures like check dams and irrigation canals enable farmers to irrigate their crops during dry seasons, thereby increasing agricultural yields and mitigating the impacts of climate change on food production.

Sustainable energy solutions: WFP engineers promote the use of renewable energy sources. In Kenya's arid regions solar-powered water pumps provide reliable access to water for both agriculture and household use (Figure 3)

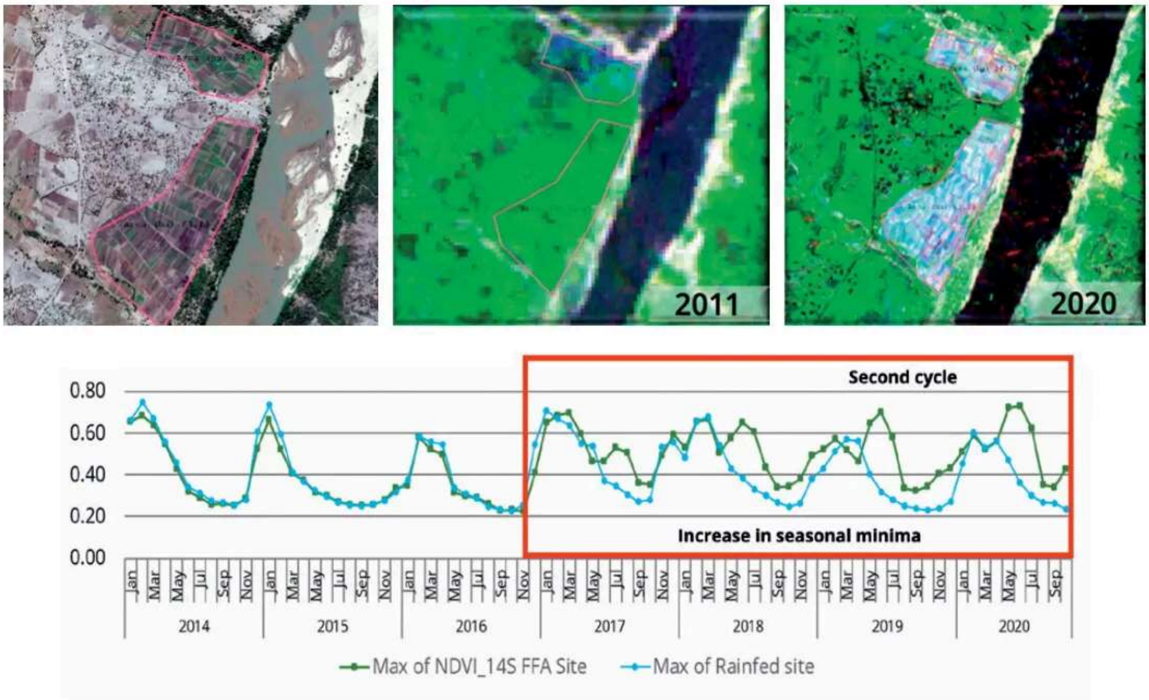


Figure 3: WFP resilience interventions are monitored by satellite data through the AIMS (Asset Impact Monitoring from Space) service. The service databases resilience project locations and monitors the built asset with very high-resolution imagery to evaluate if the asset was built to specification and is being maintained. Another service component uses data at high resolution (from the Sentinel-2 or Landsat satellites) to verify if the asset has led to the desired outcomes – in this case, the rebuilding of an irrigation scheme led to the conversion from degraded rainfed cultivation to irrigated. The plot shows that until end of 2016, locations inside and outside the new irrigation perimeter had near identical seasonal vegetation profiles. From 2017, we notice that the seasonal minimum vegetation levels increase and the appearance of a second peak in vegetation development, corresponding to off-rainfall season cultivation, which tends to be mostly of vegetables. These both improve the dietary diversity of the local population and raise household revenue from market sales.

Disaster risk reduction: Engineering interventions are essential for disaster risk reduction, protecting communities from natural disasters. This can include local flood protection infrastructures, cyclone shelters that double as community centers and storm-resistant local storage facilities.

Community involvement: Local communities are actively involved in the planning and implementation of engineering resilience projects to ensure these projects are tailored to their needs and that the infrastructure is appropriate and sustainable. WFP engineers also focus on building the capacity of local communities and governments through training in the maintenance and operation of infrastructure, as well as the development of technical skills. This capacity-building effort ensures the long-term sustainability of resilience projects and empowers communities to manage their own resources effectively.

By integrating these engineering services, WFP not only enhances the immediate response to food insecurity but also contributes to the long-term resilience and stability of food systems, thereby supporting the sustainable development of vulnerable communities.

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3. IRRIGATION ENGINEERING AND FOOD PRODUCTION

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1. Introduction

The present chapter will focus on the water use in agricultural activity, under Mediterranean edaphoclimatic conditions, with very particular characteristics, such as climatic irregularity, the absence of precipitation in the summer months, and, in many years, much rainfall in the winter months, that can require the installation of drainage systems. Despite these climatic adversities, these climatic conditions are very good, many times the best conditions, for some crops, like olives, tomatoes, grapes, dry fruits, some vegetables, and others less important (Neira et al, 2024). Considering the importance of water in these climatic conditions, this chapter will look at three realities in three different countries in the Mediterranean basin, Portugal, Spain, and Italy, which highlight the importance of using water to obtain qualified agricultural production and high yields for farmers (Zagaria et al, 2023). In addition, climate change is altering precipitation patterns, leading to longer and more frequent droughts, as well as flooding during short periods (Canatário-Duarte et al, 2022). Overexploitation of aquifers and contamination of water sources has led to a reduction in the availability of freshwater, raising serious concerns for agricultural production (Rojas-Downing et al, 2017).

The Mediterranean region is known for its agricultural diversity, where the production of crops such as olives, grapes, citrus fruits, and vegetables is essential for the local economy and the culture of the countries that comprise it. However, this region also faces significant challenges related to climate change, which affect water availability and, consequently, agricultural production. Agriculture is a key component of food security, which refers to access to sufficient, safe, and nutritious food to meet the dietary needs of a population. As the global population and food demand continue to grow, more intensive agricultural production approaches are required, especially in the Mediterranean region, where agriculture is vital for local economies. In a context where the population continues to grow, efficient water management becomes crucial to ensure food security and the sustainability of agriculture in the Mediterranean basin (FAO, 2020). Water is a vital resource, not only for crop growth but also for the livelihood of rural communities that depend on agriculture as their main source of income. Also, water is fundamental for photosynthesis, nutrient transport, and temperature regulation in plants (World Bank, 2016).

2. Irrigation and food production around Mediterranean basin

2.1. Spain, water scarcity, and sustainable and resilient water use

In the Mediterranean region, namely a great part of the mainland of Spain, where precipitation is irregular and drought is a recurrent phenomenon, the availability of water for irrigation becomes a determining factor for agricultural success. The climatic characteristics of this region, with hot, dry summers and mild, wet winters, make irrigation a necessary practice to ensure crop production and quality. Table 1 summarizes the main crops grown in the Mediterranean region and their respective water requirements.

Table 1: The main crops in the Mediterranean region (Adapted from Pereira et al., 2015).

Crop	Average Water Requeriment (mm/year)	Main Growing Season
Olives	600-800	April to October
Grapes	500-700	April to October
Citrus Fruits	800-1,200	April to November
Vegetables (e.g. tomatoes)	600-1,000	Year-round

In the period 1965-2023, the total cultivated area in Spain was reduced by 18%, although dry land was reduced by 30%, while irrigation increased by 207% compared to 1965 (provisional data for 2023). This means that dry land loses 5.7 Mha (million hectares), of which 1.9 Mha are transformed into new irrigation and 3.8 Mha are abandoned (Berbel et al, 2024). The greatest transformation is directed towards the cultivation of woody crops, which also require investments in localized irrigation. The table 2 summarizes the water balance in Spain by territorial areas.

Table 2: Water balance in Spain by territorial areas. Adapted from MITECO (2020) and Juana and Sánchez (2024).

Crop	Surface (km2)	Rainfall (mm)	Consumptive Demands hm3 (Horizon 2021)				
			Urban supply	Agricultural use	Industrial use	Others	Total consumptive uses
North and Galicia	53,780	1,429	804	413	274	5	1,496
Duero	78,960	625	263	3,485	46	8	3,802
Tagus	55,810	655	864	1,973	61	39	2,937
Guadiana	60,210	537	167	2,019	82	3	2,271
Guadalquivir	63,240	591	400	3,328	43	0	3,771
South	17,950	530	540	1,573	91	45	2,249
Segura	19,120	383	194	1,487	10	41	1,732
Júcar	42,900	504	482	2,385	153	14	3,034
Ebro	85,560	682	383	8,379	217	0	8,979
Catalonia	16,490	734	531	377	100	0	1,008
Baleares	5,010	595	139	103	3	8	253
Canarias	7,440	302	205	226	13	25	469
Spain	506,470	684	4,992	25,750	1,093	189	32,024

The current demand (MITECO, 2020) (Table 2) is estimated at 32 km3, of which 25,7 km3 (80%) is for irrigation, 4,9 km3 (16%) for supplying populations, and 1,1 km3 (3%) for industry. A distinction was made between the demand that consumes the resource, consumptive demand, and demand that only uses it. In this sense, it was estimated that 80% of that destined for irrigation was consumptive (the other 20% would return to the river network) and 20% of that destined for supplies and industry (80% would be returned).

Irrigation techniques, such as drip irrigation and sprinklers, are widely used to optimize water use. Drip irrigation, in particular, is very effective in this region, as it minimizes water waste by directing it straight to the roots of the plants. However, its implementation can be costly and requires regular maintenance, posing a challenge for small farmers in rural areas.

As climate change continues to alter climatic conditions, irrigation systems must adapt to face the uncertainty of water availability. This involves not only adopting more efficient technologies but also rethinking water management strategies and cultivating varieties of plants that are more drought-resistant.

In response to water scarcity, aggravated by the climate change projected conditions, it is crucial to implement sustainable and resilient water management strategies in the face of climate change. Integrated water resource management policies become essential to balance the needs of agriculture, human consumption, and environmental conservation. To address these challenges, various sustainable irrigation strategies are being adopted in the Mediterranean region. One of these is the implementation of precision irrigation technologies, which enable farmers to apply the exact amount of water needed for each crop based on their specific requirements (Döll and Schmied, 2012). These technologies utilize sensors, climate data, and predictive models to optimize water use and reduce waste. By integrating data on soil moisture and plant water needs, farmers can significantly reduce the amount of water used. Table 3 lists some innovative irrigation technologies and their benefits for Mediterranean agriculture.

Table 3: Irrigation technologies for Mediterranean agriculture (Own elaboration from CIHEAM, 2016 & Pereira et al. 2015).

Irrigation Technology	Description	Benefits
Drip Irrigation	Delivers water directly to the root zone through a network of pipes and emitters.	Highly efficient, reduces water waste (30-50%), increases crop yield and reduces weed growth.
Smart Irrigation Systems	Uses sensors and automation to optimize water delivery in real-time.	Reduces water waste (20-30%), prevents over-irrigation, improves plant health, and reduces labor costs.
Subsurface Drip Irrigation (SDI)	Burying drip irrigation lines below the soil surface to water roots directly.	Minimizes evaporation, prevents runoff, improves crop health, and is ideal for vineyards and orchards.
Precision Sprinkler Systems	Advanced sprinklers that control water pressure and droplet size for specific areas.	Reduces evaporation, delivers water uniformly, and benefits row crops like vegetables and cereals.
Drones for Irrigation Monitoring	Drones with multispectral cameras monitor plant health and soil moisture.	Detects water stress reduces over – or under-watering, saves labor, and improves large farm management.
Soil Moisture Sensors	Devices placed in soil to measure moisture levels and trigger irrigation automatically.	Optimizes water use, prevents over-watering, reduces water consumption (up to 50%), and enhances drip systems.
Solar-Powered Irrigation	Uses solar panels to power irrigation pumps, reducing reliance on grid electricity.	Environmentally friendly, reduces energy costs, suitable for remote areas, and ideal for small-to medium-sized farms.
Desalination for Irrigation	Desalination processes treat seawater to provide fresh water for irrigation.	Provides alternative water sources, supports drought-prone coastal agriculture, and reduces groundwater extraction.

Mulching and Cover Crops	Organic or synthetic materials cover the soil to retain moisture.	Reduces evaporation, improves water retention, reduces irrigation needs, and protects soil structure.
Aquifer Recharge & Water Harvesting	Captures rainwater and recharges aquifers for future irrigation use.	Increases groundwater availability, ensures sustainable water use and reduces.
Rainwater Harvesting	Collects and stores rainwater	Reduces reliance on groundwater improves resilience

Additionally, crop rotation and the use of cover crops are practices that can improve soil health and optimize water use. These strategies not only contribute to the sustainability of the ecosystem but can also enhance agricultural productivity in the long term (Pimentel and Pimentel, 2008). Agroecology presents itself as a viable alternative, promoting agricultural practices that mimic natural ecosystems and can better adapt to changing climate conditions.

2.2 Southern Italy, irrigation, agricultural production, and economic stability

In Italy irrigation is crucial in the agricultural sector, particularly in southern Italy, significantly impacting production and economic stability. The key points are:

- Dependence on Irrigation: Approximately 75% of agricultural production in Southern Italy relies on irrigation, making water a vital resource for farmers (Fais, 2006).

- Water Scarcity and Competition: Water is relatively scarce and unevenly distributed in Southern Italy, leading to intense competition between agricultural, urban, industrial, and tourism sectors (Fais, 2006).

- Economic Impact: Irrigation is essential for the economic viability of agriculture in the region. For instance, irrigation of arable crops in Southern Italy and the islands has increased farm income by about 12% (Capitanio et al, 2015).

- Challenges: The region faces several challenges, including groundwater overexploitation, increasing salinization, and the impacts of climate change (Dono et al, 2019). Additionally, using brackish water for irrigation due to seawater intrusion exacerbates soil salinity issues, necessitating careful management to maintain soil fertility (Phillips et al, 2008).

- Water Management: The management of water resources is highly fragmented, involving multiple local consortia and regional governments, which complicates efficient water use (Fais, 2006). Improved governance and technological solutions are also needed to optimize water use (Fais, 2006; Allouche et al, 2006).

- Climate Change Adaptation: Deficit irrigation strategies are being implemented to cope with limited water availability, particularly in citrus cultivation, which is a significant crop in the south of Italy (Bartolini et al, 2007).

In this context, Water Use Efficiency (WUE) is crucial for optimizing water resources in agriculture. It involves measuring the water delivered to irrigated plots and the amount taken from sources. Recent advancements have allowed for satellite imagery to estimate crop water consumption (Jia and Zheng, 2014).

Efficient irrigation management and scheduling are essential for improving WUE. This includes determining the optimal amount and timing of water application based on crop needs, soil characteristics, and meteorological conditions. The goal is to maximize the beneficial water use component, which is the fraction of water that can be utilized by plants. While several methods have been developed to improve WUE, their adoption is often restricted by cost, installation time, and maintenance challenges. Improving water use efficiency in irrigation can contribute to reducing environmental impact and increasing sustainability. Moreover, increasing water use efficiency can lead to higher productivity and profitability of agricultural land it can also contribute to improving the economic competitiveness of agricultural production systems (Carlesso et al, 2009).

Another critical aspect to underline is a notable dualism between the north and south of Italy regarding irrigation efficiency and management. The north, particularly the Padano district, shows lower efficiency in irrigation management for cereals and fruit compared to the more efficient practices in the southern districts like Appenino Meridionale (Capitanio et al, 2015; Dono et al, 2019). Thus, the main irrigated crops in Italy vary by region, reflecting the diverse agricultural practices and climatic conditions across the country.

The following crops are identified as significant in terms of irrigation:

Maize: Particularly in the Po Valley plain in northern Italy, maize is a major irrigated crop, covering almost 30% of the agricultural land in the region (Bechini and Castoldi, 2009).

Rice: Italy is the leading producer of rice in Europe, with traditional paddy fields primarily located in the north-western regions (Gharsallah et al, 2023; De Marco et al, 2018).

Tomato: In the Apulian Tavoliere, one of the largest irrigated districts in Southern Italy, processing tomatoes are a representative irrigated crop (Palumbo et al, 2011).

Vegetables: Various vegetable crops such as lettuce, tomato, melon, fennel, cucumber, endive, and cauliflower are grown in irrigated systems, particularly in central and southern Italy (Campanelli and Canali, 2011; Lonigro et al, 2015).

Fruit and Citrus: Fruit farming, including citrus, is also a significant part of the irrigated agricultural landscape in Italy (Bartolini et al, 2007; Bazzani et al, 2005).

Olive: In the Apulian region, olive groves are a major irrigated crop, with remote sensing techniques used to monitor irrigation practices (Matarrese et al, 2023).

These crops highlight the diversity and regional specificity of irrigated agriculture in Italy, reflecting the country's varied climate and agricultural practices. The environmental impacts of irrigated crop production in Italy are significant. Using irrigation with saline water can lead to seawater intrusion into groundwater, soil salinization, and nitrogen leaching, which poses a severe environmental threat (Campanelli and Canali, 2011). Additionally, the adoption of conservation agriculture (CA) can lead to a reduction in yield in the early years of transition from conventional to CA, but it also improves soil fertility, reduces management costs, and enhances soil carbon sequestration, thus contributing to environmental sustainability (Borsato et al, 2020). Reusing purified wastewater for irrigation can supplement water availability and limit withdrawals from groundwater, contributing to sustainable water management in agriculture across Italy (Lonigro et al, 2015; Bartolini et al, 2007).

The adoption of water conservation and saving technologies (Deficit Irrigation, DI) by Italian farmers can improve the resilience of the agricultural sector and enhance water sustainability in water-scarce locations (Bazzani et al, 2005; Matarrese et al, 2023).

The economic implications of irrigated crop farming in Italy are influenced by the introduction of green payments and the impact of climate change on farm income. The introduction of green payments may have significant negative effects on gross margin, especially for farms specialized in maize production (Cimmino et al, 2015). Farm net revenues are very sensitive to seasonal changes in temperature and precipitation, with different responses from livestock and crop farms, as well as rainfed and irrigated crop farms (Bozzola et al, 2018).

The great challenges in the irrigation of crops in Italy include the need for efficient irrigation management to prevent soil salinization and seawater intrusion into groundwater, as well as the trade-offs between human needs and the conservation of natural capital in sustainable irrigation practices (Campanelli and Canali, 20115; Matarrese et al, 2023).

Irrigation significantly impacts Italian food production, particularly in rice cultivation in the north-western part of the Padana plain (Corbari and Mancini, 2023). Moreover, the replacement of traditional flooding with water-saving irrigation techniques, such as Alternate Wetting and Drying (AWD, a type of Deficit Irrigation), has brought economic benefits to farmers and reduced irrigation needs without significantly affecting rice yield or quality (Corbari and Mancini, 2023). The use of treated wastewater for irrigation can supplement water availability and limit withdrawals from groundwater, contributing to the sustainability of Italian food production (Buttinelli et al, 2024). Deficit irrigation (DI) has been found to have contrasting effects on crop yields and irrigation water utilization efficiency (IWUE) for processing tomatoes in Mediterranean Italy, with variable results depending on climate and soil parameters (Francaviglia and Di Bene, 2019).

Regarding environmental implications of irrigation, the reuse of purified wastewater for irrigation can mitigate water shortage, support the agriculture sector, and protect groundwater resources in Southern Italy (Libutti et al, 2018). However, using treated agro-industrial wastewater for irrigation may pose challenges related to soil and product contamination, requiring careful assessment of health risks and microbiological safety (Libutti et al, 2018).

The economic and environmental analyses of different irrigation systems used in Italian beet sowing seed production identified advantages for localized irrigation, including reduced total irrigation costs and water footprint (Assirelli et al, 2023). To achieve the so-called precision irrigation, the adoption of 4.0 technologies, such as sensors for constant field monitoring, has been shown to improve water management and reduce water consumption in Italian agriculture, with positive economic implications for farmers (Stefanini et al, 2023). Implementing water conservation strategies in the tomato processing industry has resulted in considerable water savings, contributing to environmental sustainability (Eslami et al, 2024).

2.3 Alentejo Region-Portugal, modern irrigation systems, and technologies

In Portugal, this chapter will focus on the importance of a large irrigation project in the south of Portugal (Alentejo region), equipped with modern infrastructures and technologies for managing the water distribution, and precision irrigation systems, for promoting efficient water use and protecting de environment.

The Alentejo region, in the south of Portugal, corresponds to around 1/3 of the territory of mainland Portugal. It is a region with a low population density, only 5% of the population, with high rates of human desertification and aging. Its Gross Domestic Product per capita is below the national average, and it also has a large rainfall deficit. The lack of water in this region has, over the years, been one of the main constraints on its development, preventing the modernization of agriculture and the sustainability of public supply. The Alqueva Irrigation System (EFMA, acronym in Portuguese), located in the Alentejo Region (Portugal) (Figure 1), is a project centered on the Alqueva dam, the largest strategic water reserve in Europe, whose aim is the economic and social development of the region in which it is located, by guaranteeing the water resource. This hydro-agricultural development is a project based on the concept of multiple purposes, where the Alqueva dam is the center of the largest water reserve in Europe, with a total capacity of 4,150 million cubic meters. It has the size, scope, and modernity of infrastructures that make it possible to irrigate the largest Portuguese hydro-agricultural perimeter, produce hydroelectric power in reversible mode, enabling total complementarity with other renewable energies such as photovoltaics, public and industrial supply, preservation of the environment and heritage and land use planning. The Alqueva Irrigation System (EFMA) has a direct impact both on the municipalities covered by the Alqueva reservoir and on those that benefit from the installation of new irrigation perimeters or are served by public water supplies (EDIA, 2023).

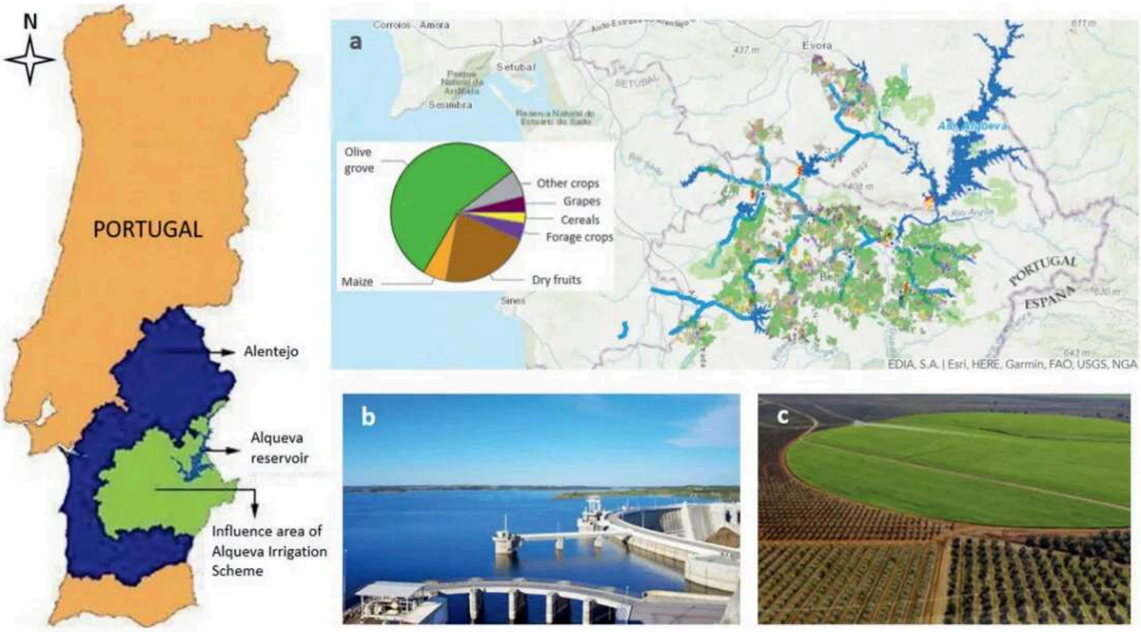


Figure 1: Location of Alqueva Irrigation Scheme influence and respective reservoir, in the Region of Alentejo (Portugal) (Rosa, 2020), actual expansion of beneficed area (a) (EDIA, 2024a), aspect of the dam and reservoir that supply the irrigated area (b) (EDIA, 2023), and example of crops in the irrigation scheme (olive groves with drip irrigation, and maize with center pivot machine) (c) (EDIA, 2023).

The Alqueva Global Irrigation System consists of 72 dams and reservoirs, 2,078 km of canals and pipelines, 48 pumping stations, 5 mini-hydro plants, and 1 photovoltaic plant, and is divided into three subsystems according to the different water sources, namely Alqueva, Ardila and Pedrógão (EDIA, 2024a).

The Alqueva subsystem, whose water originates in the Alqueva reservoir, is developed from the Álamos Pumping Station. This infrastructure allows water to be raised to a height of 90 m, through a forced pipeline 850 m long and 3.2 m in diameter, to the Álamos reservoirs, which guarantee the distribution of water to the entire Alqueva subsystem, which has a total irrigated area of around 75,000 ha (EDIA, 2024a).

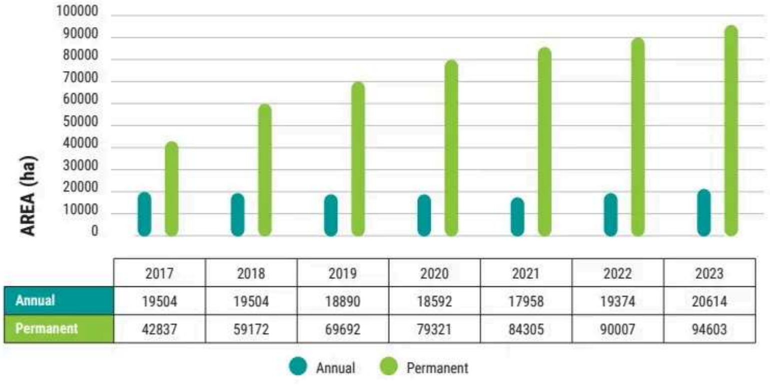
The Ardila River subsystem, with its water source in the Pedrógão reservoir and its pumping station, is made up of a set of 15 dams or reservoirs. It stretches over 60 km of primary network and has around 270 km of pipelines in the secondary network, 6 pumping stations, and a mini-hydroelectric power plant, including several irrigation schemes located on the left bank of the Guadiana River in the municipalities of Moura and Serpa, covering a total irrigated area of 30,000 ha (EDIA, 2024a).

The Pedrógão subsystem, which also draws its water from the Pedrógão reservoir and has its own pumping station, comprises a total of 9 dams or reservoirs, 3 pumping stations, more than 42 km of primary network, and adits on the right bank of the Guadiana River, and benefits an area of 24,500 ha (EDIA, 2024a).

Close to the new Aldeia da Luz, there is a 593-hectare irrigated area, that pumps the water directly from the Alqueva reservoir.

This project currently operates an area of 130,000 hectares, with an adherence rate, i.e. use of the irrigation infrastructures, of over 95%. Meanwhile, the expansion of Alqueva's irrigation perimeters is underway, covering an area of around 40,000 hectares, and demand has increased, both from farmers and from investors wishing to set up in Alqueva or establish partnerships. The investment in this multi-purpose project, now managed by the Alqueva Infrastructure Development Company (EDIA), has enabled a progressive change in the agriculture system of Alentejo, traditionally based on rainfed land, which now, with the guarantee of water from Alqueva, generates new opportunities for irrigated crops and provides opportunities for agro-industries. The irrigation perimeters of the Alqueva subsystems, equipped with modern remote management techniques, offer farmers a guarantee of water, but also the possibility of obtaining information in real-time and adapting the irrigation periods and irrigation depths to their needs at any given moment. EDIA also provides users with a tool to simulate water consumption and estimate the associated cost. The Irrigation Tariff Simulator is a simple tool that is prepared to calculate the cost associated with water consumption, depending on the location and type of supply, the crop's year of installation, the volume of water planned for the crop and the respective area benefited (EDIA, 2024b).

The Alqueva Irrigation Scheme is a national benchmark for its large area of olive groves, but also for its diversity of annual and permanent crops (Figures 2 and 3). The different soil and climate conditions, found throughout all areas of EFMA, provide good conditions to produce a diversified portfolio of crops.



	2017	2018	2019	2020	2021	2022	2023
Annual	19504	19504	18890	18592	17958	19374	20614
Permanent	42837	59172	69692	79321	84305	90007	94603

Figure 2: Evolution of land occupation by annual and permanent crops in Alqueva Irrigation Scheme (EDIA, 2023).

Olive groves are, to a large extent, Alqueva's most important crop and, in a way, the symbol of the region's new irrigated agriculture. Around 50% of the olive presses in the Alentejo region are in the Alqueva area, which demonstrates the importance of olive groves for this region and the economic importance of the olive oil sector in Alqueva.

As a result, the Portuguese olive sector has greatly increased its productivity. To technically characterize this sector, a study was produced to understand the true economic, social, and environmental impacts of this crop and to identify the conditions for promoting its sustainability. This study, coordinated by EDIA, points out that modern irrigated olive groves can be developed in a sustainable and ecologically positive way, depending on the cultural practices used. Good practices such as the preservation and promotion of pockets of biodiversity in the middle of the crop (riparian galleries, groves, isolated Quercineae, temporary ponds, living hedges, and multifunctional inter-rows), or the preference for biological pest control play a decisive role. However, in recent years other crops have expanded greatly in the Alqueva Irrigation Scheme, such as almonds, corn, and vines, which have had a more or less significant impact on regional and national production. The crops that had the greatest impact on regional production were almonds, table grapes, corn, tomatoes for industry, and olive groves, with an increase in area of 92.3%, 91.1%, 69.4%, 51.6%, and 35.3%, respectively (Table 4). In the national context, the crops that contributed most to the increase in crop area were melons, almonds, table grapes, walnuts, and olive groves, with an increase in the area of 85.3%, 37.4%, 23.8%, 19.6%, and 18.7%, respectively (INE, 2022 and EDIA, 2023) (Table 4).

Table 4: Most representative crops in EDIA, in the context of Alentejo (EDIA, 2023) and Portugal (INE, 2022) production.

Crops	**Cropped area in Portugal (ha)**	**Cropped area in Alentejo (ha)**	**Cropped area in EDIA (ha)**	**Average production in EDIA (ton/ha)**	**Authorized Application Depth in EDIA (mm)**	**Cropped area of EDIA versus Alentejo (%)**	**Cropped area of EDIA versus Portugal (%)**
Olive grove	379565	201298	71035	8–9 (vase) 12–14 (hedge)	280 (vase) 340 (hedge)	35.3	18.7
Grapes wine	173518	25391	5447	08-Oct	210	21.5	3.1
Maize grain	74639	10369	7197	14-16	780	69.4	9.6
Almonds	63884	25857	23859	2-3 (kernel)	570	92.3	37.4
Wheat and Triticale	31046 15354	22766 13798	1434 338	04-May	300	6.3 2.5	4.6 2.2
Citric fruits	21765	1806	576	15-20	600	31.9	2.7
Tomato-industry	15193	1888	974	90-100	670	51.6	6.4
Dystic Barley	11932	9667	1422	4	260	14.7	11.9
Sunflower	7668	5951	1216	4	450	20.4	15.9
Walnuts	5492	1950	1077	02-Apr	700	55.2	19.6
Grapes table	2273	593	540	25-30	520	91.1	23.8
Melon	1730	------	1476	25-35	500	------	85.3
Onion	1574	------	342	20-30	760	------	31.7

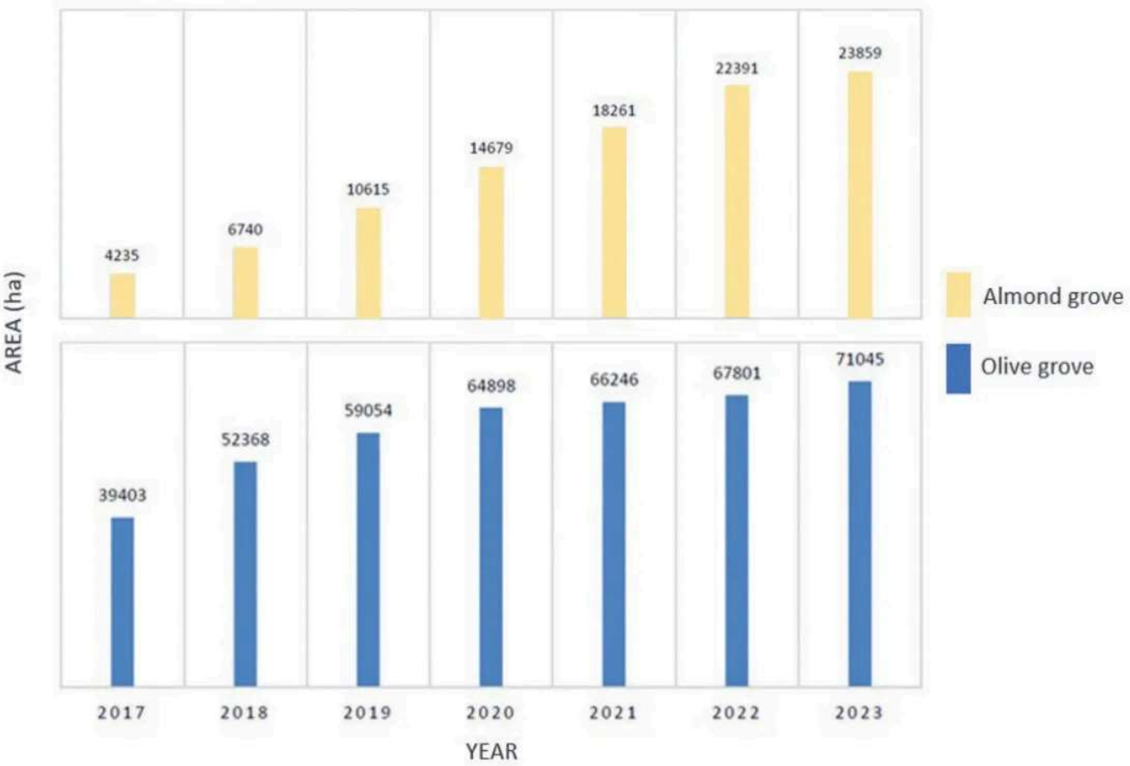


Figure 3: Evolution of land occupation by almond and olive groves (2017-2023) (EDIA, 2023).

In 2022, EDIA the water price for irrigation in the subsystems of the Alqueva Global Irrigation System, was the following. The Conservation Rate is defined as the fee applied to all owners benefiting from irrigation, even if they don't use the water for irrigation, and the Operating Rate is defined as the fee applied to owners of areas benefiting from irrigation who actually use the water for irrigation. Precarious users are those who irrigate areas outside the benefited areas, with water from the irrigation scheme (Government Order 3025/2017, 11 April 2017).

- Water taken directly from the primary network, with pumping provided by the farmers: 0.0305 €/m3;
- Water taken from the Secondary Network to supply high-pressure water to farms (≥ 3.0 bar):
- Conservation Rate: 55.91 €/ha;
- Operating Rate: 0.0599 €/m3;
- Water taken from the Secondary Network to supply low-pressure water to farms (< 3.0 bar):
- Conservation Rate: 20.33 €/ha;
- Operating Rate: 0.0325 €/m3;
- Precarious users:
- Water supply with high pressure (≥ 3.0 bar): 0.0783 €/m3;
- Water supply with low pressure (< 3.0 bar): 0.0387 €/m3.

The conversion from extensive to intensive farming, and from rainfed to irrigated farming, has led to a change in farming practices with greater use of resources and production factors, with repercussions for the environment and human health. In this context, EDIA has drawn up a Manual of Good Agri-Environmental Practices, as a tool to support and help all farmers of the Alqueva Irrigation Scheme, thus contributing to the adoption of correct and sustainable environmental behavior. The monitoring of the environment is also an important management tool, making it possible to characterize the reference situation and follow the evolution of the different environmental descriptors. EDIA's Environmental Management Program, approved in 2005, provides the promotion, coordination, and implementation of environmental monitoring programs, which ensure (EDIA, 2020):

- Monitoring and understanding the evolution of environmental variables in the influence area of the Alqueva Irrigation Scheme;
- Collect and compile data to support decision-making in the management and operation of irrigation scheme;
- Evaluate the effectiveness of the mitigation measures implemented in the various environmental areas and, if necessary, propose new measures;
- Assessing the status of surface and groundwater water bodies;
- Assessing the biodiversity of fauna and flora;
- Monitoring the evolution of properties that contribute to good soil health.

3. Conclusions

The Mediterranean edaphoclimatic conditions, with very particular characteristics, such as climatic irregularity, the absence of precipitation in the summer months, and, in many years, much rainfall in the winter months, are often climatic adversities, but, at the same time with the practice of irrigation, these conditions are very well, for some crops, like olives, tomatoes, grapes, dry fruits, some vegetables, and others less important.

So, irrigation and water management are essential aspects of agricultural production and food security in the Mediterranean region. The implementation of sustainable irrigation technologies, along with efficient agricultural practices, can contribute to a more responsible and effective use of water. Collaboration among different stakeholders, including farmers, governments, and non-governmental organizations, is crucial for developing policies and strategies that promote sustainability. Efficient irrigation is crucial for agricultural production in this context, as it allows farmers to maximize crop yields. However, the impacts of climate change, such as rising temperatures and decreased water availability, threaten this capability. Sustainable agricultural practices, coupled with efficient water management, are essential to mitigate the effects of climate change and ensure food security in the region. Crop diversification and the promotion of native varieties are strategies that can also help increase the resilience of agricultural systems to adverse climate conditions.

Normally, irrigation has both positive and negative impacts on food production, affecting yield, quality, the environment, and the economy. Adopting water-saving irrigation techniques and using treated wastewater for irrigation can contribute to sustainability, but careful assessment of health risks and economic efficiency is essential. Therefore, adopting advanced irrigation technologies can improve water management and contribute to environmental sustainability.

The main irrigated crops in Italy include maize, rice, meadows, winter cereals, fruit, vegetables, citrus, tomato, and processed tomato products. The environmental impacts of irrigated crop production are significant, with challenges such as seawater intrusion, soil salinization, and nitrogen leaching. The irrigation system contributes to sustainability by reusing purified wastewater and adopting water conservation and saving technologies. Key challenges in the irrigation of crops in Italy include efficient irrigation management and the trade-offs between human needs and the conservation of natural capital in sustainable irrigation practices.

In Portugal, the Alqueva irrigation project is exemplary in many aspects, related to water management and distribution to farmers, environmental monitoring and protection, water pricing, and the location of the chain value inside the region where are located the irrigation project. This irrigation project has a modern management system, based on remote sensing, to regulate the water distribution on the canals and pipes network, according to the water demand by the farmers. It is a very important question to save water in the irrigation project. The relatively low price of water allows the farmers to obtain profits more high, and become more competitive. The Alqueva Irrigation Project has a true concern with environmental questions, like control of fish species transference between different watersheds, control of invasive plant species (freshwater hyacinth), that can disturb the water flow in the canals, advice the farmers to rational use of water fertilizers. Inside the influence area of this irrigation project are located many agro-food plants to transform, process, and pack, the crop production of this great irrigated area.

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3.a. CASE STUDY: WATER REUSE IN CITRUS FARMING - CARBON EMISSIONS REDUCTION AND ECOSYSTEMS PROTECTION

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1. Introduction

Anthropogenic factors and climate change are putting increasing pressure on natural water resources, threatening habitats and biodiversity (Libutti et al.2018, Rebelo et al., 2020). Worldwide, agriculture uses around 70% of the total water used in human activities. In addition, the demand for food and animal feed production tends to increase with the growth of the world population (Parris, 2010; Becerra-Castro et al., 2015; Chartzoulakis & Bertaki, 2015; Karandish & Šimunek, 2016). Meanwhile, freshwater use has exceeded recharge levels, leading to the desiccation of water streams, and the groundwater over-extraction has promoted saline intrusion phenomena in several coastal areas, posing additional constraints to agricultural irrigation, decreasing production and lowering crop yields (Jenkins & Sugden, 2006). To face this scenario, agriculture sustainability in more vulnerable regions, such as the south of Portugal, where water scarcity is a common reality, involves the choice of an alternative water supply and more efficient irrigation systems (Fatta-Kassinos et al., 2011; Jiang et al., 2016), as well as crop selection. To ensure the water demands of the human population are met without threatening the ecosystems, it is necessary to reduce the extraction of natural water and the discharge of treated effluents into the environment (Santana et al., 2019). The current technological advances in the wastewater treatment plants (WWTP) often allow the use of reclaimed water as a safe water source for different purposes, such as for the irrigation of some crops (Bixio et al., 2008; Garcia & Pargament, 2015; Nas et al., 2020). Nitrogen, phosphorus and potassium, present in treated effluents, can reduce the use of synthetic fertilizers (Becerra-Castro et al., 2015; Fatta-Kassinos et al., 2011; Adrover et al., 2012), contributing to the decrease in N_2O and CO2 emissions (Syakila et al., 2010; Chojnacka et al., 2019). However, water reuse may pose risks to public health and the environment, due to the possible existence of pathogenic microorganisms and toxic chemical compounds, such as disinfection products and emergent pollutants (Rebelo et al., 2020; Becerra-Castro et al., 2015; Fatta-Kassinos et al., 2011). In recent years, several European countries, including Cyprus, Greece, France, Italy, Spain, and Portugal, have been updating the legal framework (Portuguese Law 119/2019) for water reuse for multiple non-potable purposes, based on risk assessments. Thus, urban water reuse is considered as a safe process, provided that the treated effluents' risk framework management and the quality standards (based on physicochemical and microbiological parameters) are adequate for the proposed use (Rebelo et al., 2020; Becerra-Castro et al., 2015; EPA, 2012). For fruit trees, such as citrus trees, not in direct contact with irrigation water, the risks of transmission may be lower than for vegetables, which grow in direct contact with the soil and irrigation-reclaimed water (Becerra-Castro et al., 2015; Cirelli et al., 2012; Melloul et al., 2001). Citrus trees are native to Southeast Asia, but have been present in the Mediterranean basin for centuries and have become part of the Mediterranean diet, being used as fresh fruit, as well as in various dishes and desserts (Duarte et al., 2016). Located in southernmost area of Portugal, the Algarve region has a hot-summer Mediterranean climate, according to the Köppen climate classification, and presents a semi-arid coastal zone (Hugman et al., 2015; Estrela et al., 1996). Citrus fruits are the main Algarve crop, corresponding to a production of 368,000 t in 2020 (INE, 2022) of which 316,000 t were oranges. In general, agriculture accounts for 12% of the total greenhouse gas (GHG) emissions by human activities (IPCC, 2014), due to diverse field practices, including irrigation and fertilization. The sustainable management of these practices is considered to be the most promising mitigation pathway to reduce GHG emissions from agricultural soils [Liu et al., 2011; Scheer et al., 2012). In the Mediterranean, the use of drip-fertigation is increasing, particularly in high-value crops such as orchards (Brouwer et al., 19899, constituting an important practice for the efficient water and fertilizer use, and the reduction in production costs. Conversely, traditional irrigation and fertilization practices are responsible for N_2O emissions between 30% and 50% higher than fertigated crops (Kennedy et al., 2013; Shcherbak et al., 2014) due to the excessive application of nitrogen in traditional practices which led to higher nitrification rates (Shcherbak et al., 2014). However, agriculture has the potential to remove atmospheric carbon and orchards can function as carbon sinks, contributing to the mitigation of GHG emissions (Sahoo et al., 2021; West & Marland, 2002). Citrus orchards are considered to have a high carbon sequestration potential (Núñez-Florez et al., 2019), and the trees' ages were identified as a major determinant for the carbon potential sink capacity of such systems (Mo & Zang, 2012). This study assessed the feasibility of the use of treated urban effluent in citrus orchard irrigation as an alternative to groundwater and evaluated the respective environmental benefits.

2. Materials and Methods

This work was performed between March and July 2019 at the Algarve region, where agriculture is the biggest water user, and water scarcity is severe during most months of the year. The WWTP, which treated the effluent used in this study, is in Faro (37°01'04''N; 7°57'30''W), was built in 1989 and improved in 2009 to serve between 34,100 and 45,500 equivalent inhabitants, according to population fluctuations, mainly due to the seasonality of tourism.This WWTP is managed by the company responsible for the urban wastewater treatment, Águas do Algarve, S.A. (AdA)—Águas de Portugal Group, and is located inside the Ria Formosa Natural Park, a shallow coastal lagoon. The WWTP has a preliminary treatment with an automatic screening system, followed by removal of oil and grease by mechanical separation. There are two lines of biological secondary treatment by activated sludge process (ASP), each one consisting of an anoxic selector followed by an aerobic/anoxic reactor (carrousel type) and a circular decanter. The disinfection is carried out after secondary sedimentation with a UV system, and the treated effluent is discharged into a channel of the Ria Formosa. The discharge standards and the monitoring results of the treated effluent, reported by AdA, between January 2016 and November 2018 are presented in Table 1. Considering the existence of an orange (*Citrus sinensis*) orchard ('Valencia Late' grafted on 'Troyer' citrange) next to the WWTP, with 3397 trees in about 9.5 ha, we evaluated the feasibility of using the treated effluent for irrigation. This is an orchard with drip irrigation, with groundwater from the Campina-Faro aquifer. This aquifer is about 86.4 km^2 and presents a mean recharge of about 10 hm$_3$ year^{-1}, mostly by precipitation. The water of this aquifer often presents high concentrations of chlorides due to saline intrusion phenomena, and of nitrates resulting from intensive agricultural practices (Almeida et al., 2000; Nunes et al., 2006). The irrigation system presents two tubes along each row of trees, with dripper spacing of 0.75 m and 2 L.h^{-1} discharge rate. The application of synthetic fertilizers is by fertigation and during the experimental period pesticides were not applied.

Table 1: Characteristics of the treated effluent reported by AdA from Jan 2016 to Nov 2018.

Parameter	Limit Values Discharge Permit	Min-Max Average ± SD
Biochemic. Oxygen Demand, 20°C ($mg\ L^{-1}\ O_2$)	25	<5[1]-11 <5[1]
Chemical Oxygen Demand ($g\ L^{-1}\ O_2$)	125	18-110 34±11
Total Nitrogen ($mg\ L^{-1}$ N)	Not Applicable	<3[1]-34 11.3±7.8
Total Phosphorous ($mg\ L^{-1}$ P)	Not Applicable	<0.50[1]-5.3 1.4±0.9
Total Suspended Solids ($mg\ L^{-1}$)	35	2-33 5±4
Faecal coliforms (MPN 100 mL^{-1})	100	3-260 103±75
Influent Flow Rate ($m^3\ day^{-1}$)	-	4585±996

[1] Limit of Quantification.

At the beginning of the experimental period, the chemical properties of the soil were characterized, dividing the orchard in three sectors (I–III in Figure 1) and collecting three samples, by sector, of the surface soil (0–10 cm) for further laboratory analysis. In the laboratory, the nine soil samples were air dried, ground on an agate mill and sieved over a 2 mm sieve. For each orchard sector, were quantified: texture of the fine earth material (<2 mm) was determined by Boyoucus method of densimetry (Day, 2015); organic matter (OM) by titrimetric by Walkley–Black method (Schumacher, 2002); total nitrogen (TN) by the Kjeldahl method (Bremner, 1960). The water extracts were obtained after the pre-treatment for wet analysis with distilled water. The pH and electric conductivity (EC) were quantified by electrometry, for pH using the Metrohm 780 pH meter in a 1:2.5 suspension of soil in water (ISO 10390:2021) and for EC using the WTWinolab level 2 with the TetraCon 325 in a 1:2 suspension of soil in water (EN 13038:1999). Chlorides (Cl-) were quantified by the titration Mohr method (Hesse, 2022) in a 1:5 suspension of soil in water. Phosphates (P_2O_5) were determined after Egner–Riehm extraction, by molecular absorption spectrometry (Baird et al., 2017). For boron (B), the azomethine-H spectrophotometric method (Sarkar et al., 2014) was used after extraction in Morgan's solution (Sims, 2011). Calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) were extracted by the ammonium acetate method (Schollenberger & Simon, 1945), and for iron (Fe), copper (Cu), manganese (Mn), molybdenum (Mo) and zinc (Zn), the Lakanen–Erviö extraction method (1971) was used. After extraction, metals were quantified by atomic absorption spectrometry (Baird et al., 2017), Ca, Fe, Mg, K, Na and Zn by flame, and Cu, Mn, and Mo by graphite furnace. The sodium adsorption ratio (SAR) was calculated. To assess whether there were significant differences ($p < 0.05$) in the soil characteristics between the different orchard sectors, a one-way ANOVA test was performed for a 95% confidence interval, using SPSS 26 (IBM, Armonk, NY, USA). After this, was used the Tukey test to check if there was any relationship between the sectors and the detected differences. The groundwater (GW) used for orchard irrigation, and the treated effluent (TE) were sampled monthly, between March and July 2019, and three replicates of each sample were collected for further analysis in the laboratory according to Table 2. We performed one-way ANOVA test for a 95% confidence interval, to assess whether there were significant differences ($p < 0.05$) over time for all parameters.

Table 2: Analytical methodology used to GW and TE characterization (Baird et al., 2017).

Parameter	Method	GW	TE
Ammonia (mg L^{-1} NH_4^+)	Molecular absorption spectrometry. SMEWW 4500-NH_3 F [41]	✓	✓
BOD5, 20oC (mg L^{-1} O_2)	Respirometric method. SMEWW 5210 D [41]	✗	✓
B (mg L^{-1})	Molecular absorption spectrometry. LAE -7.10.3 [46]	✓	✓
Ca, Fe, Li, Mg, K, Na (mg L^{-1})	Flame atomic absorption spectrometry	✓	✓
	SMEWW 3111 B	✓	✓
	[41]	✓	✓
Chlorides (mg L^{-1} Cl^-)	Argentometric method. SMEWW 4500 Cl^- B [41]	✓	✗
EC, 20 ºC (µS cm^{-1})	Electrometry. SMEWW 2510 B [41]	✓	✓
Phosphates (mg L^{-1} P)	Molecular absorption spectrometry, SMEWW 4500-P E [41]	✓	✓
Mn, Mo, Se, V (mg L^{-1})	Graphite furnace atomic absorption spectrometry SMEWW 3113 B [41]	✗	✓
Fluorides (mg L^{-1})	Electrometry. SMEWW 4500-F^- C [41]	✗	✓
Nitrates (mg L^{-1} NO_3^-)	Molecular absorption spectrometry, SMEWW 4500-NO_3 B [41]	✓	✓
Oxidability (mg L^{-1} O_2)	Titrometry. LAE - 9.1	✓	✗
pH (Sorenson scale)	Potentiometry, SMEWW 4500-H^+ B [41]	✓	✓
Sulphates (mg L^{-1} SO_4^{2-})	Molecular absorption spectrometry, LAE -7.50.2 [46]	✓	✓
Total Dissolved Solids (mg L^{-1})	Gravimetry. SMEWW 2540 C [41]	✓	✓
Total Suspended Solids (mg L^{-1})	Gravimetry. SMEWW 2540 B [41]	✓	✓
Turbidity (NTU)	Turbidimetry. ISO 7027:2019	✗	✓
Escherichia coli (CFU 100 mL^{-1})	Membrane filtration. [47]	✓	✓

During the wastewater treatment there are two types of greenhouse gas emissions (GHG) related to WWTP functioning, the direct and indirect emissions from all processes in the plant. Direct emissions refer mainly to N_2O, CH_4, and CO_2 emissions, usually generated by microbial metabolic activities during wastewater treatment and sludge treatment/disposal processes. Indirect carbon emissions result from the energy in operation and resources (Mo & Zang, 2012; Parravicini et al., 2022; Li et al., 2022). Previous studies, based on the data reported by EU Member States compliant with the Urban Wastewater Treatment Directive (UWWTD 91/271/EEC) made available by the European Environment Agency, estimated that direct N_2O emissions and indirect electricity emissions are the main contributors in the operation phase, followed by direct CH_4

emissions. Analyzing various scenarios to reduce emissions, it was demonstrated that the efficient use of electricity at the plant and the decarbonization of electricity would significantly help to improve the CO_2 e footprint of the WWTP [50]. Similar to most WWTP emission protocols, this study does not include the direct GHC emissions, as these GHG are emitted to the atmosphere through the natural process of decomposition anyway (Mo & Zang, 2012; Crawford et al., 2011). Attending to the specific energy consumption of Faro-Noroeste WWW(KWh/m^3), reported by AdA, we calculated the carbon emissions (CE) related to the treatment of the necessary volume of effluent for citrus irrigation, during the experimental period. To evaluate the impact of treated urban effluent reuse on the CE, we compared the CE related to both sources of water for citrus irrigation: (1) Considering the current irrigation dose during the experimental period, the energy consumption to groundwater extraction for irrigation was compared with the energy consumption for transporting the treated effluent from the WWTP to the orchard, assuming the same characteristics of the currently installed pump (submersible with a flow rate of 30 m^3 h^{-1} and 7.5 kW). Then, we calculated the CE related to both energy consumptions, considering the carbon emission factor for electricity in Portugal during 2019, 248.65 g CO2eq kWh-1 (EDP, 2020), including emissions of CO_2, CH_4, and N_2O; (2) Attending to the amount of synthetic N and P-fertilizers applied by fertigation during the experimental period (when groundwater was used for irrigation), and to the nutrient concentrations (N and P) in the treated effluent, we calculated the necessary adjustment of synthetic fertilizers, to ensure the same nutrient supply to the citrus trees. The CE related to the different amounts of synthetic fertilizers applied in both irrigation conditions was quantified using the CFP of N and P-fertilizers production in Europe at plant gate, calculated according to ISO 14067 [53] (N-fertilizer CFP = 1.14 kg CO_2e/kg and P-fertilizer CFP = 0.71 kg CO_2e/kg). The CE related to the transportation of fertilizers was not considered in these calculations.

3. Results and Discussion

The characteristics of the soil are presented in Table 3. The ANOVA test showed significant differences ($p < 0.05$) for all parameters. According to the Tukey test, for levels of pH, Phosphorus, Magnesium, organic matter, Iron, Manganese, Calcium and Molybdenum, sectors II and III do not present significant differences between them, but they present significant differences to sector I. The soil texture in sector I is sandy clay loam and in sectors II and III is loamy sand. As expected, clayey soil is richer in OM and, therefore, in P and N. Higher pH and higher Ca concentrations are associated with lower Fe bioavailability.

Table 3: Chemical soil properties (average standard deviation). Values with different letters (a, b and c) are significantly different at $p < 0.05$.

Parameter	Sector I	Sector II	Sector III	Mean Sectors I, II, III
pH	8.4a±0.1	7.6b±0.1	7.5b±0.1	7.8±0.5 *
EC, 20 ºC (dS m^{-1})	2.90a±0.06	1.99b±0.01	6.62c±0.04	3.84±2.12 *
TN (mg kg^{-1} N-NH$_4^+$)	624a±12	448b±36	520c±28	531±80 *
Cl- (mg kg^{-1})	676a±71	193b±183	534a±97	468±241 *
B (mg g^{-1})	0.60a±0.04	0.57b±0.03	0.67c±0.04	0.61±0.05 *
P_2O_5 (mg kg^{-1})	689a±71	403b±17	477b±17	523±134 *
OM (% m.m^{-1})	1.4a±0.1	1.2b±0.1	1.1b±0.1	1.2±0.2 *
Ca (mg kg^{-1})	560a±8	345b±18	382b±3	429±100 *
Fe (mg kg^{-1})	39.0a±1.4	78.3b±5.5	78.1b±1.9	65.1±19.8 *
Cu (mg kg^{-1})	14.1a±0.3	14.2a±0.6	19.1b±0.7	15.8±2.5 *
Mg (mg kg^{-1})	493a±2	247b±2	250b±2	330±122 *
K2O (mg kg^{-1})	1092a±7	932b±10	1261c±26	1095±143 *
Na (mg kg^{-1})	48.3a±2.9	14.2b±0.6	44.5a±1.1	35.7±16.3 *
Mn (mg kg^{-1})	30.6a±0.9	22.7b±1.5	23.9b±0.6	25.7±3.8 *
Mo (mg kg^{-1})	1.25a±0.02	2.10b±0.15	2.45b±0.02	1.93±0.54 *
Zn (mg kg^{-1})	13.8a±0.2	12.4b±0.4	14.4a±0.2	13.4±0.9 *

* There are significant differences at ANOVA test

Between March and July 2019, the local mean atmospheric temperature was 19.3 °C, with a minimum of 12.8 ºC (March) and a maximum of 32.0 ºC (June). The local precipitation was below 5 mm, and from June the percentage of water in the soil was less than 20% (IPMA, 2019).Between March and July 2019, the local mean atmospheric temperature was 19.3 C, with a minimum of 12.8 ºC (March) and a maximum of 32.0 ºC (June). The local precipitation was below 5 mm, and from June the percentage of water in the soil was less than 20% (IPMA, 2019). The total groundwater consumption for orchard irrigation during the experimental period was 27,891 m3. The water consumption per month increased from the coldest month (March) to the warmer months (June and July), according to Figure 1. This figure also shows the consumption in the same months of the previous two years, as well as the mean per month over the three years.

The results of groundwater monitoring during the experimental period, and maximum recommended values (MRV) in Portuguese legislation, are summarized in Table 4. In general, all parameters in groundwater showed lower values than MRV, except for electrical conductivity (1.45±0.04 dS m^{-1}), chlorides (395±138 mg L^{-1} Cl^{-}) and TDS (1044±163 mg L^{-1}). These results seem to confirm the occurrence of saline intrusion phenomena in the Campina-Faro aquifer, as reported before, e.g., by Nunes et al. [36]. During the experimental period, there were significant differences ($p < 0.05$) for all parameters over time, confirming the seasonality effect, except for oxidability and sulphates. The oxidability values were very low (1.3±0.7 mg L^{-1} O^{2}) over all months and sulphate concentrations remained stable throughout the experimental period (217±18 mg L^{-1} SO_4^{2-}).

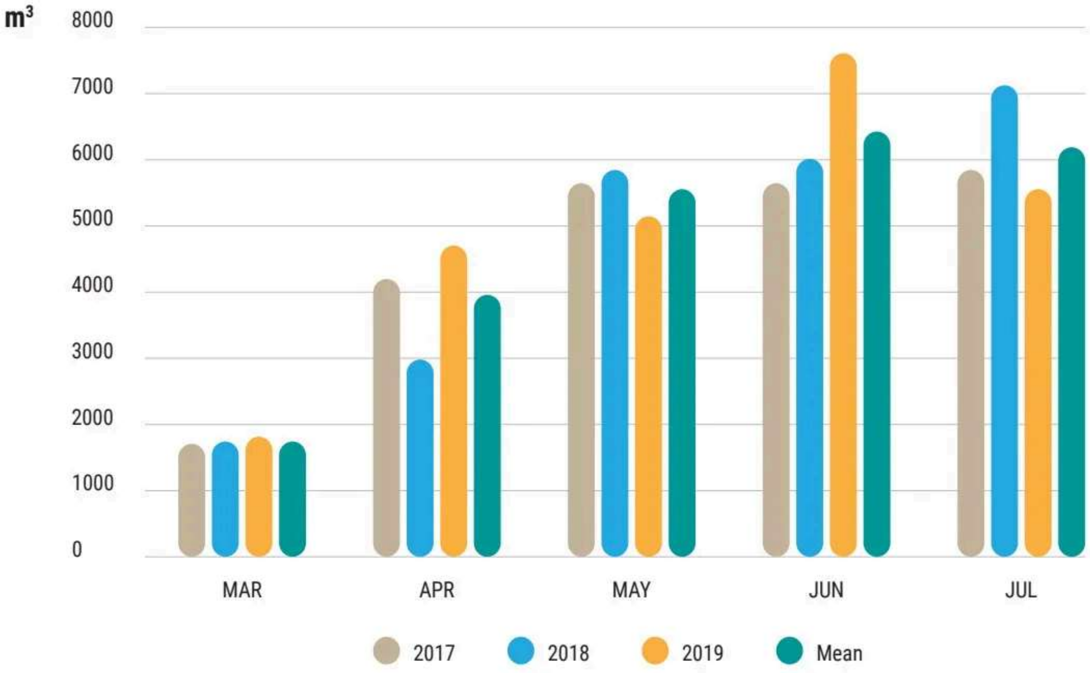

Figure 1: Evolution of groundwater consumption for orchard irrigation during the experimental period, similar months in 2017 and 2018, and mean per month.

Table 4: Chemical characterization of GW and TE throughout the experimental period experimental period (average ± standard deviation).

Parameter	Groundwater	Natural Water for Irrigation MRV (1)	Treated Effluent (TE)	Water Reuse QS(2)
Ammonia (mg L-1 NH_4^+)	0.023 ± 0.020	--	3.92 ± 1.59	10
BOD5, 20 ºC (mg L^{-1} O_2)	7	--	10.1 ± 5.3	≤25
B (mg L^{-1})	0.08 ± 0.02	0.3	0.16 ± 0.03	--
Ca (mg L^{-1})	52.5 ± 1.1	--	34.1 ± 1.1	--
Fe (mg L^{-1})	✗	5.0	0.44 ± 0.03	2.0
Li (mg L^{-1})	✗	2.5	0.11 ± 0.01	2.5
Mg (mg L^{-1})	51.2 ± 11.4	--	34.9 ± 7.0	--
K (mg L^{-1})	35.6 ± 19.4	--	23.4 ± 11.7	--
Na (mg L^{-1})	123 ± 6	--	142 ± 25	--
Chlorides (mg L^{-1} Cl^-)	395 ± 138	70	311 ± 94	--
EC, 20 ºC (dS m^{-1})	1.45 ± 0.04	1	1.29 ± 0.23	--
Phosphates (mg L^{-1} P)	<0.125(3)	--	0.5 ± 0.34	5 (Total Phosphorous)
Mn (mg L^{-1} Mn)	✗	0.20	0.02 ± 0.01	0.2
Mo (mg L^{-1})	✗	0.005	0.21 ± 0.15	0.01
Se (mg L^{-1})	✗	0.02	<0.01(3)	0.02
V (mg L^{-1})	✗	0.10	<0.01(3)	0.1
Fluorides (mg L^{-1})	✗	1.0	0.15 ± 0.02	2.0
Nitrates (mg L^{-1} NO_3^-)	<4(3)	50	4 ± 1	15 (Total Nitrogen)
Oxidability (mg L^{-1} O_2)	1.3 ± 0.7	--	✗	--
pH (Sorenson scale)	7.41 ± 0.17	6.5-8.4	7.87 ± 0.14	--
SAR	3.6 ± 0.8	8	4.1 ± 0.6	--
Sulphates (mg L^{-1} SO_42^-)	217 ± 18	575	171 ± 15	--
TDS (mg L^{-1})	1044 ± 163	640	830 ± 166	--
TSS (mg L^{-1})	1.0 ± 0.8	60	3.5 ± 1.8	≤35
Turbidity (NTU)	✗	--	7.5 ± 2.4	--
Escherichia coli (CFU/100 mL)	0 to 2	100	2 to 100	≤100

– not referred; X not quantified; (1) maximum recommended value in Portuguese Law 236/98, Annex XVI; (2) quality standards in Portuguese Law 119/2019 and EU Regulation 2020/741, for fruits not in direct contact with irrigation water [54]; (3) limit of quantification.

The overall volume of treated effluent produced by the WWTP, during the experimental period was about 619,359 m^3, 22 times higher than the volume of groundwater consumed for irrigation. The specific energy consumption on the WWTP during the experimental period was 0.77 $kWh.m^{-3}$, meaning that 118,583 kg CO_2e were emitted. Figure 2 presents the monthly variation on treated effluent production during the experimental period and in the same months of the previous two years, as well as the mean per month over the three years.

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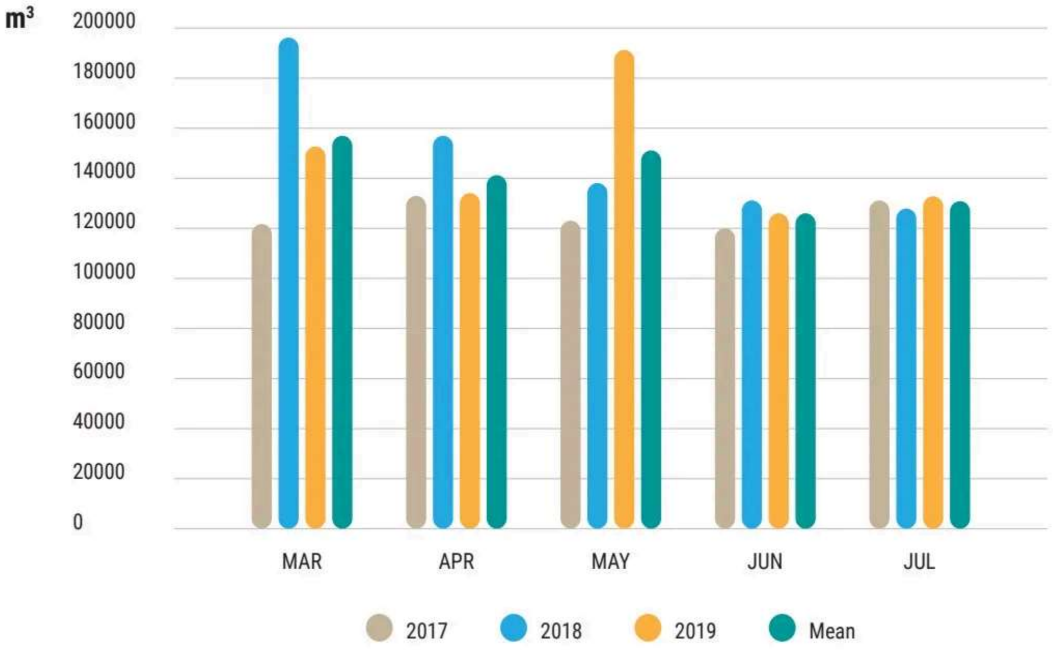

Figure 2: Evolution of treated effluent production during the experimental period, on similar months in 2017 and 2018, and mean per month.

Table 4 also shows the characteristics of the treated effluent and Quality Standards, for water reuse in fruit tree irrigation. All parameters meet the quality standards, except for molybdenum and total dissolved solids. Molybdenum can reach the wastewaters from diverse anthropogenic sources, such as metallurgical processing, coal and petroleum burning or discharges of phosphate detergents. Molybdenum is an essential micronutrient for plants, but toxic if present in high concentrations. The soil properties its availability, the molybdenum phytotoxicity being greater in alkaline soils, and in dicotyledonous species (McGrath et al., 2010). Despite this, under natural conditions there is no reference to the toxicity of molybdenum in citrus trees. The treated effluent presented a higher organic matter content than the groundwater (in TE: BOD = 10.1±5.3 mg L-1 O_2 and in GW: oxidability = 1.3±0.7 mg L^{-1} O_2), suggesting that the use of TE can have a positive effect on soil organic carbon and on its water retention (Becerra-Castro et al., 2020; Baldock & Sparks, 2003; Nelson, 2000). Attending to the ammonia (3.92±1.59 mg L^{-1} NH^{4+}), nitrate (4 2 mg L^{-1} NO^{3-} and phosphate (0.57±0.34 mg L^{-1} P) concentrations, it is expected that the discharge of the treated effluent into Ria Formosa may cause eutrophication phenomena. Alternatively, if this treated effluent is used for irrigation, then it contributes to increasing the N-forms and P-forms in the soil. Efficient irrigation and fertilization practices can be an important contribution to the ecosystem's sustainability and agriculture development (Li et al., 2020). These results confirmed that the use of the treated effluent for irrigation, with higher nutrient levels than groundwater (phosphorous and nitrogen), instead of being discharged into the Ria Formosa lagoon, can be used for supply, at least a part, of the crops requirements, as reported before in other studies (Becerra-Castro, et al., 2020). The quantified values for E. coli are compatible with the water reuse for the irrigation of fruit trees, and the risk of contamination is even lower when using a drip irrigation system which means that the irrigation water does not come into contact with the aerial part of the plant. Although in the Portuguese legal framework E. coli is proposed to be the "hazard" indicator as it is the most suitable indicator of fecal contamination, the water quality is not considered the only parameter that can ensure health protection in water reuse projects. The adoption of other preventive measures to reduce hazards and exposure to hazards must be identified, i.e., barriers to minimize contact with reclaimed water and recognized receptors. The irrigation type and schedule, harvest options, and crop characteristics can limit the contact between people and pathogens present in reclaimed water. Previous studies showed that drip irrigation of high-growing crops, 50 cm or more above the ground, allows a 4 log10 pathogen reduction meaning 2 equivalent barriers (Rebelo et al., 2020). These studies were carried out in a vineyard irrigated with reclaimed water from an urban WWTP, where grapes are used exclusively for wine production, therefore in conditions not very different from a citrus orchard. Regarding the conductivity of the irrigation water, it is recommended not to use water with an electrical conductivity greater than 3 $dS.m^{-1}$; the adjusted sodium adsorption ratio should be less than 9 and the chloride ion concentration less than 355 mg L^{-1}. It is also not recommended to use water with boron concentrations above 0.75 mg L^{-1}.

The production of oranges was 117.3 t (25 t ha^{-1}), which is considered a relatively low yield for a 30-year-old orchard, but consistent with the relatively small size of the trees. Orange production is considered to contribute to GHC mainly due to the CO_2 and CH_4 emissions on the production of synthetic fertilizers and to the N_2O emissions from soil denitrification during the agricultural practices (Ribal et al., 2009). In our work, we calculated the CE per kg of harvested oranges, considering the contribution of synthetic fertilizers production and the energy consumption in pumping water for irrigation, during the experimental period (Table 5).

Table 5: Carbon emissions related to the energy consumption in pumping water for irrigation and orchard fertilization.

Water source for irrigation	Energy consumption in water pumping (kW)	Synthetic fertilization		Carbon Emissions	
		N-fertilizer (Kg)	P-fertilizer (Kg)	kg CO_2e	g CO_2e / kg^{-1} of oranges
Groundwater	3449	870	733	858.968	7.32
Treated effluent	1734	76.7	683	431.662	3.68

Our results show that the wastewater reuse allows for a significant reduction in CE related to orange production, minus 50% for the water pumping for irrigation, minus 91% for the N-fertilizer and minus 7% for the P-fertilizer, which means minus 3.64 g CO^2e. kg^{-1} of harvested oranges and a reduction of 427.306 kg CO_2e per total orange production, during the experimental period. These results show that wastewater reuse in citrus orchards irrigation can contribute to more sustainable food production. Previous works (Mordini et al., 2009) presented the carbon footprint of oranges produced in Spain, Italy and Brazil, showing that the values vary considerably from

80 to 330 g CO_2e per kg of harvested oranges. In our work, the carbon emissions per kg of harvested oranges present lower values because we only quantified the CE directly related to the replacement of groundwater by the treated effluent in orchard irrigation. The N_2O emissions due to the agricultural practices, not considered in this study, will be relevant to the carbon footprint and similar in both irrigation conditions. Previous studies in eastern Spain (Núñez-Florez et al., 2019) reported that an adult citrus tree (over 12 years old) can fix a net carbon amount higher than 73.29 kg CO_2 tree^{-}1 yr^{-}1 and total biomass of the annual organs accounted for more than 70% of this value, specifically, harvested fruit. According to this reference, we estimated that during the five-month experimental period, the carbon sequestration in biomass was about 30.55 kg CO_2 tree^{-1}, representing about 103,747 kg CO_2 sequestered by the orchard of which 72,623 kg of CO_2 was converted into orange biomass. These results indicate that this orchard has sequestered 87.5% of the carbon emissions related to the energy consumption necessary for the urban wastewater treatment, highlighting its importance in reducing the WWTP impact on GHC emissions.

4. Conclusions

This study shows that treated effluent reuse is technologically feasible for citrus orchards irrigation and can contribute to improving the carbon fluxes, reducing GHC emissions, and promoting carbon sequestration. According to our results, the GHC emissions related to orange production can decrease, mainly due to the reduction in energy consumption of water pumping for irrigation, and the need to apply a smaller amount of synthetic fertilizers, since the treated effluent presents higher concentrations of nitrates and phosphates than groundwater. In addition, although further studies are needed, this alternative source of water for citrus irrigation presents other benefits for natural ecosystem protection.

The use of reclaimed water prevents the overexploitation of coastal aquifers, reducing saline intrusion and, at the same time, reducing nutrient discharges into the Ria Formosa, avoiding eutrophication phenomena in this coastal lagoon, classified as a Ramsar site. Since the organic matter content in the treated effluent is higher than in groundwater, it is expected that the use of reclaimed water promotes water retention in soil, improving plant growth and thus carbon sequestration. This improvement in the carbon sequestration by the citrus orchard will increase fruit production and the farmer profits. Finally, this work highlights the great potential of citrus orchards to sequester GHC emitted by the urban WWTP, and its potential contribution to the carbon neutrality of the urban wastewater treatment.

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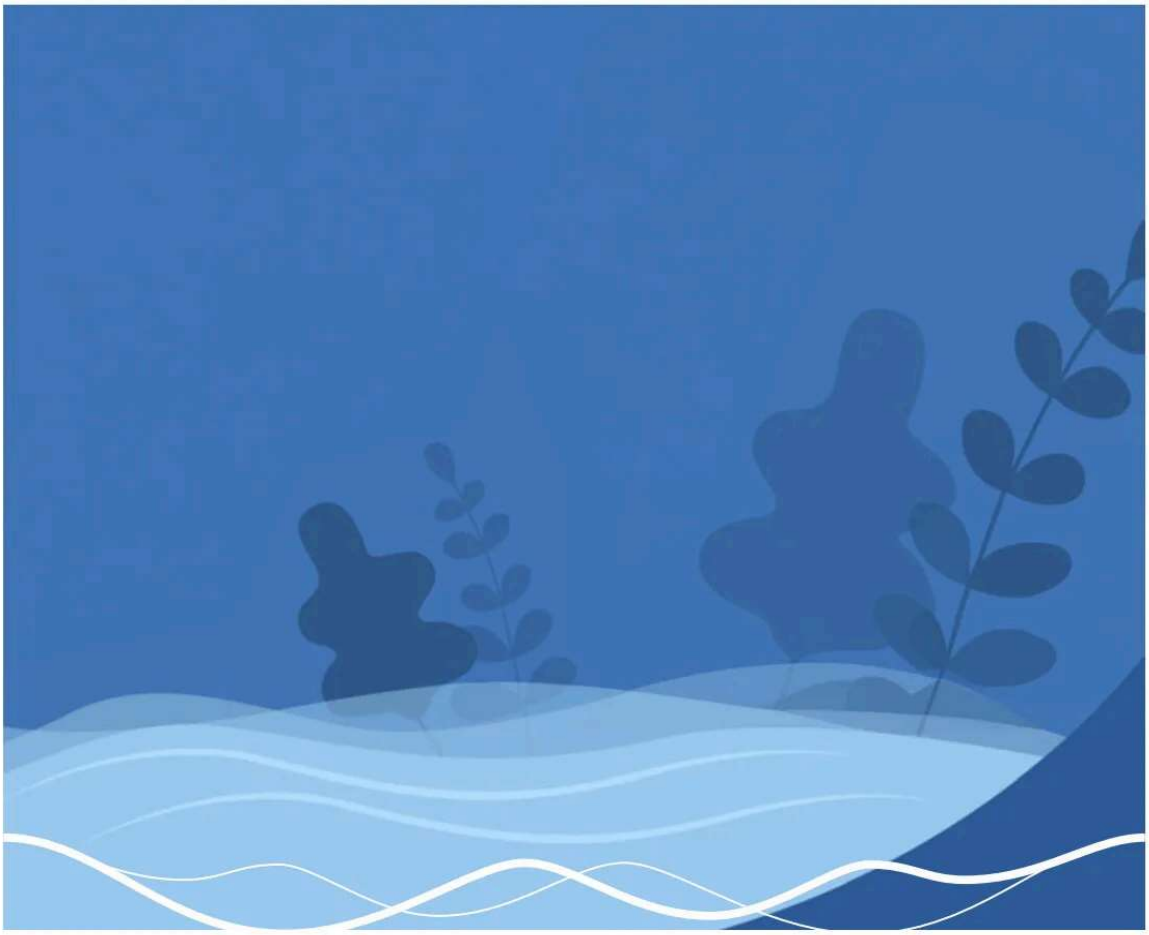
3.b. CASE STUDY: MANAGEMENT OF PUBLIC IRRIGATION SYSTEMS IN MOROCCO: CHALLENGES AND INNOVATIONS FOR RESILIENT AGRICULTURE



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[4] He leads research on assessing the sustainability of the Global North's water footprint in Morocco's fresh produce exports, contributing to Water Witness's efforts to promote sustainable and equitable water use. With over 7 years of experience in integrated water resources management and climate change adaptation, Ismail has led large-scale projects in rural development, water management, and infrastructure planning across government and international organizations. He has collaborated with organizations including the Green Climate Fund, IFAD, and ICID, supporting water governance, rural livelihoods, and climate resilience.

[5] He obtained his PhD at the age of 27 from the University of Franche-Comté (France) and his Doctorate of state from Cadi Ayyad University (Morocco) in 1995. He has been Senior Professor at Ibn Zohr University (Morocco) since 1995. His research focuses mainly on "the contribution of chemical and isotopic tracers to water resource management in semi-arid zones, water and soil salinity, karst hydrology, environment, climate change and its impact on natural resources in arid zones". He is Leader of several national and international research contracts (EU, IAEA, UNESCO, NATO, EU, CNRS, CNRST, IRD, ABH, ACADEMIE Hassan II, OCP, etc.) since the 1990s, and supervises some 30 PhD candidates. He has published more than 200 scientific papers in reputed journals, has been a reviewer member of reputed journals and an international expert in the field of water resources. He was former president of the Moroccan chapter of the International Association of Hydrogeologists (IAH) from 2003 to 2016. He has been an Affiliated Professor at the International Water Research Institute (IWRI) at Mohammed VI Polytechnic University (UM6P) since July 2019.

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1. Introduction

Morocco, characterized by a semi-arid climate over 93% of its area, relies on irrigation for agricultural productivity, with 88% of water resources used to irrigate 1.6 million hectares (DIAEA, 2024). The irrigation supports 45% of agricultural production in average years in terms of inflows and over 70% in dry years, providing 33% of rural jobs and contributing to 75% of agricultural exports (DRPE, 2024). Despite significant infrastructure investments, Morocco faces increasing water scarcity due to climate change, population growth, and socio-economic development (Guemouria et al. 2023). To address these challenges, Morocco has implemented the "Green Generation (2020-2030)" plan, continuing efforts from the "Green Morocco Plan (2008-2020)" and emphasizing the National Irrigation Water Saving Program (PNEEI) (Guemouria et al. 2024). Efficient water use has become a priority, with drip irrigation covering over 500,000 hectares, representing about 43% of irrigated land (Lionboui et al. 2022). Irrigation techniques in Morocco include surface irrigation, pressure irrigation (sprinkler and micro-irrigation), and underground irrigation (Simonneaux et al. 2009). Surface irrigation, the oldest method, still dominates, covering over 70% of irrigated land. However, modernization efforts, particularly integrated in the PNEEI, aim to expand drip irrigation to 550,000 hectares (Brouziyne et al. 2022). Effective irrigation management combines soil, climate, and plant data, with methods varying based on crop species, the development cycle, and the irrigation technique (Belaqziz et al. 2013). Despite advancements achieved, challenges in irrigation water management persist. This study seeks then to address these challenges by comparing new and traditional irrigation methods, analyzing crop yield responses to deficit irrigation, and exploring modeling applications for efficient plot-level water management.

2. Material and Methods

This article analyzes research studies on irrigation water management for major crops in Morocco. Data were obtained by searching in the Web of Science and Scopus databases using the keywords "Irrigation", "Water management", "Agricultural resilience" and "Morocco". Several scientific articles were identified from the initial search on Scopus and Web of Science. By focusing on crop water requirements, the comparison between new and traditional irrigation techniques, the response of crop yields to deficit irrigation and the application of modelling for efficient water management at plot level, it was possible to limit the number of scientific articles reviewed. In order to enrich our database and carry out an in-depth analysis, we included reports from the national institutions explaining the irrigation situation in Morocco.

3. Results

3.1. Methods for improving water productivity in Morocco

In Morocco, supplemental irrigation, mainly used for cereals covering more than 5 million hectares, is essential in arid and semi-arid zones where annual rainfall is irregular (200-400 mm) and droughts frequent (Guemouria et al. 2023). It involves applying small quantities of water at critical times to stabilize and improve crop yields, while saving water. Experiments carried out in several regions (Chaouia, Abda, Doukkala, Saïss, Gharb, Tadla) have confirmed its effectiveness (Karrou and Boutfirass, 2000). Deficit irrigation optimizes water use by targeting drought-critical growth phases, while other periods receive little or no irrigation. This technique, which stabilizes yields at safe levels while maximizing water productivity, requires a good understanding of crop response to water stress (Duchemin et al. 2006).

Three main strategies are used:

- continuous: constant water supply below total requirements;
- regulated: reduced input during less sensitive phases,
- partial root zone drying: alternate watering of different parts of the root system (Kharrou et al. 2011).

Genetic approaches aim to select crop varieties that are tolerant to water stress and productive. The selection of genotypes with optimal growth cycles and harvesting dates improves water use efficiency by maximizing rainfall exploitation during critical growth phases (Jarlan et al. 2015).

3.2. Irrigation of the main crops in Morocco

Research on citrus irrigation in Morocco, particularly in Tadla, Al Gharb and Moulouya regions, has focused on managing water deficit and optimizing irrigation practices (Lahlali et al. 2021). On the sandy soils of Al Gharb, localized irrigation has improved water quality and reduced water consumption by 40% (Beniken et al. 2013). In the Tadla region, an irrigation regime using 80% ETc optimized the yield and quality of "Maroc Late oranges", with an average of annual water requirements of 1,073 mm (Abdelhak et al. 2021). Varieties and rootstocks have a significant influence on citrus physiological and biochemical processes, with some rootstocks (Citrus macrophylla, Citrange Carrizo) showing high water use efficiency. Olive trees tolerate water deficit well, but beyond a certain threshold, growth and yield decrease, although oil quality improves with an increase in phenols (Ezzahar et al. 2009; Er-Raki et al. 2010).

Experiments in Meknes and Marrakech have shown that a regulated deficit irrigation (70% ETc during critical phases and 50% ETc during less critical phases) can maintain yields over 3 to 4 years without significant impact (Aouade et al. 2020). However, a more severe deficit irrigation (50% ETc from April to October) reduces yield by 20% in the first year of application (Ibba et al. 2023). Irrigation of date palms is often excessive, reaching 180-300% of actual needs (Khardi et al. 2024). Optimal management, with inputs adjusted to 60%, 100%, and 80% of ETc in winter, spring, and summer respectively, achieved a 14% water saving while improving yields (Sabri et al. 2017). Regulated Deficit Irrigation (RDI) regimes have been tested for almond, peach, plum, and apple trees. These regimes, applied during non-critical growth phases, maintained yields and improved certain biochemical attributes of the fruits while saving water (Molle and Tanouti, 2017).

Supplemental irrigation is crucial for wheat in the arid and semi-arid regions of Morocco, enhancing grain yield and water use efficiency (Bouras et al. 2019). Irrigation during critical stages (tillering, heading, grain filling) is particularly beneficial (Bouchaou et al. 2017). Alfalfa yields, influenced by water quantities and irrigation duration, range from 0.64 to 2.57 kg/m^3 depending on seasons and water stress levels (El Moussaoui et al. 2024). Water use efficiency decreases with water stress (Elhassnaoui et al. 2019). Water deficit significantly affects silage corn, reducing growth, leaf area index, and dry matter yields. Water use efficiency is highest during the linear growth phase.

Comparative studies have shown that micro-irrigation saves 17-38% water and increases yields by 51-100% compared to flood irrigation (Guemouria et al. 2023). The response of sugar beet to water stress and nitrogen fertilization indicates that optimized irrigation regimes (up to 60% ETc) and specific nitrogen doses can maintain good root yield despite water stress conditions (Rerhou et al. 2024). Optimizing irrigation through techniques such as localized irrigation and regulated deficit irrigation enhances water use efficiency, maintains yields, and improves crop quality in the context of limited water resources (Elhassnaoui et al. 2021).

3.3. Analysis of new irrigation techniques in Morocco

In Morocco, drip irrigation can increase crop productivity and save water compared to flood irrigation (Elhassnaoui et al. 2023). However, its adoption is low due to high investment and operational energy costs. To address this, new low-pressure drippers are being tested. A study by Boularbah et al. (2019) compared the hydraulic, energy, and agronomic performance of conventional drippers (CD) operating at 1 bar and low-pressure drippers (LP) at 0.15 bar. Conducted over three years in citrus orchards in Tadla and olive trees in Marrakech, the results showed LP drippers reduced hydraulic energy by 43% without significantly affecting water distribution uniformity (80-92% for LP vs. 88-97% for CD).

Growth parameters, yield, and fruit quality of the "Maroc late variety" were similar for both dripper types, indicating LP drippers as a viable substitute for conventional ones. In Sous Massa and Taroudant, Elame et al. (2017) found LP drip systems improved water productivity for potatos (11.36 kg/m^3) and increased yields for zucchini, eggplant, peppers, and olives by 7.14, 5.59, 4.50, and 0.28 kg/m^3, respectively, with up to 69% yield improvement and 47% water savings. Technological advances in irrigation have led to the development of porous tubes, including nanotubes (Moistubes), which provide efficient water delivery to plant roots. These tubes, featuring tiny perforations, ensure controlled water supply at low pressure, reducing waste and disease risk (Abioye et al. 2020).

Although still experimental, INRA Morocco has conducted lab and field tests at Melk Zher, examining water dynamics and flow in different soil types and densities (Moussadek 2022). Findings suggest that soil structure and compaction affect flow rates, necessitating careful design for depth and spacing. Field comparisons between nanotube and drip systems showed no significant water consumption difference for quinoa but notable water savings for panicum, with both crops demonstrating improved biomass production. Cost analyses indicated that crop row spacing significantly influences installation costs, with wider spacing suitable for tree crops. Low-pressure irrigation and nanotube systems are promising innovations for improving water use efficiency and crop productivity in water-limited environments, with careful design considerations necessary for optimal performance.

3.4. Modelling applied to irrigation management: biophysical models and their advantages

Implementing strategies to enhance water use efficiency in agriculture requires numerous, often costly and lengthy experiments (El Harraki et al. 2021). Traditional experimentation cannot cover all irrigation scenarios or account for climate change impacts over time (El Harraki et al. 2020). Modeling offers a solution to explore water use scenarios efficiently (Tanji and Boutaibi, 2023). Biophysical models, which describe biomass production based on plant-resource interactions (solar radiation, CO2, water), have evolved from detailed, process-specific models (e.g., SIMED, ALFALFA) to more generic and adaptable ones. These models fall into three categories based on biomass production modules:

- **Carbon-driven models:** Biomass production linked to carbon assimilation during photosynthesis. Examples include WOFOST (developed for global food security studies) and CROPGRO (initially for legumes, now expanded to other crops). These models are complex with many parameters.

- **Radiation-driven models**: Biomass production based on solar radiation interception efficiency. Examples are CERES, EPIC, and the simpler PILOTE model.

- **Water-driven models:** Biomass production proportional to plant transpiration efficiency. These models, like AquaCrop (developed by FAO) and CropSyst, have fewer input parameters and are suitable for larger spatial and temporal scales.

4. Conclusion

This study presents a synthesis of the main results of research carried out in different agricultural production zones in Morocco. The aim is to disseminate best practices in irrigation water management in the field, balancing crop productivity and sustainability with water conservation. These results will provide a valuable basis for strengthening agricultural resilience and mitigating the effects of climate change. It is essential to make the knowledge acquired available to development services and to help farmers adopt it to improve the resilience of Moroccan agriculture in the face of climate change.

5. Acknowledgments

The authors acknowledge the invaluable help of those who contributed to the research effort. We would like to thank the Moroccan Ministry of Higher Education, Scientific Research and Innovation and the OCP Foundation for funding this work as part of the APRD research program - GEANTech project. L. Bouchaou also acknowledges the support of the CHARISMA project, the IRD Representation in Morocco and the AGREEMed project.

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4. WATER AND FOOD INDUSTRIES

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1. Introduction

The food sector heavily depends on water, an essential resource that serves various purposes, spanning from primary production to the entire food supply chain, and eventual consumption. It is an important food ingredient and plays a vital role in processing operations and maintaining cleanliness and sanitation of products at every step of the food chain. To ensure food safety, the food processing sector typically uses potable water from various sources, including surface water, groundwater, rainwater, and even seawater, subject to treatment to meet quality standards for food processing.

Meeting the needs of the growing global population, projected to reach 9.7 billion by 2050 (UN DESA, 2022), poses a significant challenge for the food industry. This challenge, coupled with the impacts of climate change and changing consumer demands, places additional stress on water resources, as increased food production requires more water inputs. Industrial water usage is expected to quadruple by 2050 (UNESCO, 2015; Oki & Quiocho, 2020) and recent data indicates that water scarcity will become more pronounced in the coming years (Piesse, 2020).

In addition to being a significant consumer of water, the food industry is also known as a major contributor to environmental pollution due to its substantial generation of wastewater. This wastewater originates from various technical processing operations, as well as activities such as rinsing and cleaning. Additionally, it results from the creation of by-products, which often contain a mixture of nitrogenous organic compounds, organic carbon, suspended solids, dissolved solids, and inorganic substances. This combination of factors makes the food industry a notable source of pollution in terms of wastewater discharge.

It is undeniable that the food processing industry poses a threat to the world's limited freshwater resources. Failure to take urgent mitigation measures to address these problems could result in severe consequences such as rising food prices, food shortages, environmental pollution, famine, social unrest, and geopolitical instability (Goldenberg, 2014). Given the food industry's heavy reliance on freshwater resources and its significant contribution to wastewater generation, it is crucial to examine how various food processing industries utilize water. It is equally important to assess rational and sustainable water usage practices and explore technologies that can facilitate water recycling and reuse to alleviate water stress. This chapter focuses on six food processing industry groups, namely:

- Meat and meat products
- Fish and seafood
- Dairy
- Fruit and vegetables
- Edible oils
- Beverages

In addition, this chapter will explore the water-related challenges confronting the food industry at present and examine various potential strategies for reducing the food industry's water usage and environmental impact.

Meat and meat products

Animal meat is one of the primary sources of nutrition for the human diet. Meat-derived products tend to be good source of protein that contains essential amino acids and exceptional digestibility. In the year 2021, chicken, pig, and cattle meat were produced in highest quantity worldwide, accounting for 316 million tons with an estimated value of 897 billion US dollars (FAO, 2022a).

Meat processing encompasses a series of steps, starting with the slaughter of animals, followed by meat cleaning and cutting, quality assessment, and the transformation of meat into various products like burger patties, ham, sausages, or packaged meat. Among these meat processing steps, there are specific stages that necessitate a significant water input. The quantity of water utilized within the meat industry is subject to substantial variation which depends greatly on the type of product undergoing processing. According to Fatima et al., (2021), poultry production facilities typically require approximately 11.5 liters of freshwater per animal. In contrast, buffalo production facilities exhibit a notably higher average water demand of 1,114 liters per animal, predominantly allocated for washing purposes (Shende et al., 2022).

The primary water-intensive phase in meat production involves evisceration, accounting for 44% to 60% of the overall water usage. Following this, offal washing utilizes 7% to 38% of the water supply, while 9% to 20% is dedicated to casings processing, which includes tasks like washing fat, removing blood, clearing meat residue, and eliminating hair from the casings. The second most water-intensive stage is meat cleaning, which consumes 25% to 50% of the total water consumption (Fornarelli et al., 2017). Pre-washing of the animals requires 7% to 22% of the water and is typically accomplished using water sprays or within water pools (Fornarelli et al., 2017).

To decrease water usage within the meat processing sector, it is worthwhile to explore practical operational approaches. Fasting animals prior to slaughter leads to a reduction in their gastrointestinal content, lowering the risk of visceral rupture and facilitating the cleaning of their intestines and stomachs. As a result, the overall water requirement is reduced (Kupusovic, 2007). During hot and dry seasons, air conditioning units can be employed in reception pens instead of water sprinklers to maintain a cool temperature for the animals. Dry cleaning methods can also be implemented before using water. For instance, larger solid debris can be removed using brooms or shovels, resulting in a 20-30% reduction in water consumption at this stage alone. Subsequently, a final rinse can be carried out, during which cleaning personnel aim to target the floor and surfaces at an angle of up to 60° to enhance cleaning efficiency (UNEP, 2000 as cited in Bailone et al., 2022). While immersion scalding is currently the most widely used method in slaughterhouses, alternative techniques achieving the same objective with less water usage exist. These include scalding methods employing hot water spray, steam, or condensation, which offer more efficient and controlled water utilization (Bailone, 2021).

Fish and seafood industries

Fish and seafood products are abundant sources of protein, various vitamins, and essential minerals like calcium, phosphorus, iodine, and magnesium. They are also notably rich in polyunsaturated fatty acids, including docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), which are crucial for brain function ((Benjamin et al., 2018; Kris-Etherton et al., 2002; Rimm et al., 2018). Over the last seven decades, the total production of fisheries and aquaculture has expanded significantly, rising from 19 million tonnes (live weight equivalent) in 1950 to a record of approximately 179 million tonnes in 2018, exhibiting an annual growth rate of 3.3 percent. About 90% of this production is allocated for human consumption, with the remaining 10% used for non-food purposes like fishmeal, fish oil, and ornamental fish (FAO, 2022b).

Out of the global seafood production, only 45% is consumed as fresh fish, while the remaining 55% undergoes processing and is consumed as frozen fish (29%), canned fish (14%), and cured fish (12%) (Pedro and Nunes, 2007 as cited in Murali et al., 2021). Fish processing serves two main objectives: maintaining the quality of fish from catch to market distribution and transforming fish flesh into market-desired products. Common methods of fish processing include chilling and freezing, salting, smoking, drying, and canning.

The seafood processing industry requires a significant volume of water to ensure proper storage and hygiene conditions to prevent product spoilage. Major areas of water usage encompass seafood cleaning, washing, cooking, freezing and thawing, brine preparation, equipment and floor cleaning, as well as storage and transport (Henriksson et al., 2018 as cited in Murali et al., 2021). On average, around 11 cubic meters of water are consumed per ton of prepared fish, and a majority of it is discharged as wastewater (Queiroz et al., 2013). According to BIM (2017), the fish processing stage accounts for the highest water consumption at 42%, followed by cleaning operations at 38% in the seafood industry. Excluding the water in the product, the remaining water is allocated to other on-site services like washroom sinks, toilets, and canteen sinks.

Implementing water optimization strategies, such as automating water flow systems, treating wastewater, recycling and reusing water, and continuously monitoring water usage patterns, as well as employing dry-cleaning processes, can lead to significant water savings in the industry (Murali et al., 2021). Moreover, adopting best practices can substantially reduce water consumption. For instance, in fish slaughtering, techniques like using high-pressure hoses and flow controllers can significantly decrease water usage (Bailone et al., 2022). In fish processing, switching from a continuous water flow system to a batch system, which involves immersing fish in ice water, can conserve water. The use of pressure nozzles during fish processing and cleaning can lead to water savings, and removing unnecessary nozzles during the filleting process can reduce water consumption by 60-75%. Additionally, during the thawing of fish, techniques like immersion in a water container mixed with bubbling air can provide better temperature control and reduce the need for water renewal (Valta et al., 2016).

Dairy Processing Industry

Milk and its derivatives, including cheese, cream, butter, yogurt, evaporated, powdered, and condensed milk, are rich in nutrients, providing energy and high-quality protein along with essential micronutrients like calcium, magnesium, potassium, zinc, and phosphorus in a readily absorbable form (Muehlhoff & FAO, 2013; Rizzoli, 2014; Pfeuffer & Watzl, 2018). According to OECD-FAO (2022), global milk production, comprising roughly 81% cow milk, 15% buffalo milk, and 4% from goat, sheep, and camel sources combined, increased by 1.1% to reach approximately 887 million metric tons in 2021. This growth was primarily attributed to increased output in India and Pakistan. The majority of dairy production is consumed in the form of fresh dairy products, which are either unprocessed or subject to minimal processing such as pasteurization or fermentation. Due to the distinctive characteristics of dairy products, their production processes vary, and certain phases may or may not be necessary (Asgharnejad, 2021).

The dairy sector has a significant impact on water consumption and the generation of wastewater (Vourch et al., 2005). Roughly 2 to 4 liters of water are required per kilogram of dairy products, while the volume of wastewater produced varies between 0.5 and 20.5 liters, depending on the composition and types of the final products (Palhares & Pezzopane, 2015; Ridoutt et al., 2010 as cited by Asgharnejad, 2021). Water plays a pivotal role in various aspects of dairy production, including technological processes, cleaning systems, cooling systems, steam generation, fire protection systems, and even non-industrial purposes. The specific water usage can vary based on the level of advancement and modernization of production facilities, as well as the adoption of new technologies. It is worth noting that the Cleaning in Place (CIP) system is responsible for the highest wastewater production, often containing elevated levels of fat and protein (Bortoluzzi et al., 2017).

Effective water management in the dairy industry revolves around ensuring the appropriate water quality for different processes. Depending on the water's quality and the specific technical requirements of each application, adjustments are necessary to tailor the water to various needs (Fleifle et al., 2014). These modifications may include actions such as removing color, softening the water, or introducing chlorine to reduce the presence of potential spoilage microorganisms. In certain instances, ultraviolet (UV) radiation may be employed to disinfect stored water immediately before its utilization as an ingredient in dairy products (Casani et al., 2005).

CASE STUDY 1: Utilizing whey-recovered water as a water conservation method in Cleaning-in-Place (CIP) systems for the dairy industry in the United States (Meneses and Flores, 2016).

This study highlights the potential to reclaim high-quality water from whey, a highly pollutant byproduct of cheese-making, for reuse in cleaning-in-place systems. Results demonstrated that by employing a combination of ultrafiltration and reverse osmosis, 47% of the water can be effectively recovered. Moreover, this integrated system yields protein and lactose concentrates, which, upon spray-drying, meet the commercial standards required for protein and lactose powders. Thorough analysis of the physicochemical and microbiological attributes of the reclaimed permeate was also conducted, indicating that it possesses suitable qualities for reuse in cleaning-in-place.

Fruits and Vegetables

Fruits and vegetables are packed with dietary fiber, vitamins, and minerals, making them integral to a healthy human diet. These products are commonly consumed in their fresh state or processed into high-value items such as beverages, jams, jellies, concentrates, dried goods, frozen products, and canned items. The market for processed fruits and vegetables reached a value of over $320 billion in 2022 and is projected to exhibit a compound annual growth rate (CAGR) of more than 5.5% between 2023 and 2032 (Global Market Insights, 2022). Whether in their natural state or during processing, water plays a crucial role in essential steps to ensure product safety and quality. In fruit and vegetable processing facilities, water serves multiple purposes, including being an ingredient, an energy carrier, a means of in-line transport, and a vital component for washing to maintain raw material cleanliness and production hygiene (Trajer et al., 2021).

In the fresh produce sector of fruits and vegetables, water is primarily employed for washing operations. This includes the initial wash to remove visible contaminants, a series of successive immersions of the produce in washing tanks, and a final rinsing stage. Depending on the type of produce, the total water consumption for washing fruits and vegetables typically ranges from 1.5 m^3 to 5.0 m^3 per ton of the final product (Lehto et al., 2014). Primary washing is not only important for eliminating field debris but also for removing chemicals used for pest control during farming, such as insecticides and microorganism control agents (Gil et al., 2009, as cited by Bailone et al., 2022). Water is also used for cleaning processing equipment. When combined with domestic use, water for these purposes constitutes 12% of the total water consumption in the industry (Manzocco et al., 2015).

Furthermore, water is employed as a medium for transferring fresh produce from one processing stage to another within the same facility, a common practice in processing apples and potatoes. This water-based transportation method minimizes the risk of physical damage that could adversely affect product quality and shelf life (Kader, 2002). Additionally, water is necessary for blanching and cooling fruits and vegetables when required, and it helps maintain high relative humidity to prevent produce from drying out.

CASE STUDY 2: Water Footprint in the UK Vegetable Sector (Frankowska et al., 2019).

Out of 11 million tons of vegetables consumed in UK, around 40% are imported vegetables mostly from water-stressed countries wherein farm production is the main contributor to total water footprint. Duet to its origin, it has higher water impact compared to locally grown vegetables wherein the processing stage contributes highest water footprint. At the sectoral level, beans and carrots have the highest impact on water aspect. The study concluded that the reduction of the water impact while ensuring food security must be considered by the food manufacturers and policy makers.

The water used during the washing process is typically released as wastewater, and this substantially contributes to the water footprint of fruit and vegetable processing. To alleviate the strain on water resources, the industry employs various strategies. For instance, water is recycled during the initial stage of fresh produce washing by reducing the frequency of water replacement or by treating the spent water for reuse. The concentration of chemicals used for sanitation is also adjusted to minimize water consumption while maintaining their effectiveness. Additionally, cost-effective techniques like ultraviolet (UV) treatment serve as alternative approaches.

CASE STUDY 3: Reduction of water consumption in a French frozen carrot processing plant using membrane technology (Garnier et al., 2020).

Results showed that wastewater generated from peeling of carrots can be pretreated by double sieving steps using 169 μm and 79 μm, followed by microfiltration (0.5 μm). This pretreatment is necessary to remove larger particles and prevent clogging of membranes for succeeding treatment steps. Moreover, reverse osmosis using ESPA 4 membrane can produce high quality water with low conductivity. Since wastewater from blanching operations includes the same components, the same treatment is predicted to be applicable. The treated wastewater was deemed more suitable to be reused prior to the blanching step which can serve as a thermal hurdle and ensure microbiological safety. On the other hand, demineralization was observed in water treated with reverse osmosis.

Edible Oil

Edible oils play a significant role in meeting the essential dietary requirements for fatty acids, vitamin E, and specific phytochemicals needed for daily human physiological functions (Zhao et al., 2021). They are also integral components of everyday cooking, enhancing the taste and extending the shelf life of food. These oils can be categorized as either natural, sourced from seeds, vegetables, or animals, or synthetic, which are artificially created fats. Among these options, natural oils, particularly those derived from seeds and vegetables, have gained popularity due to their reduced health risks and simpler production processes, as compared to synthetic fats (Hamm et al., 2013).

In the 2020-2021 period, the total global production of vegetable oil reached 210.94 million tons. Notably, palm oil (75.95 million tons) and soybean oil (59.46 million tons) emerged as the leading contenders in the global vegetable oil market (Japan Oil Seed Processors Association, 2023). Moreover, global demand is also increasing. This escalating trend for edible oil can be attributed to population growth, increased food consumption in developing nations, improved living standards, and evolving dietary preferences.

The extraction of edible oil from seeds and vegetables involves a multi-stage process with three primary phases: pretreatment (preparation), pressing (extraction), and refining. Among these phases, pretreatment and refining stand out as the primary stages that consume significant amounts of water and generate wastewater in the oil extraction process. Freshwater is primarily required for process applications, steam generation, cooling, and washing. To illustrate, the production of one ton of palm oil requires approximately 2.45 cubic meters of water, while soybean oil production consumes around 3.365 cubic meters. On the other hand, the corresponding wastewater generated amounts to 0.87 cubic meters and 8.5 cubic meters, respectively (Asgharnejad, 2021).

Typically, wastewater generated by the edible oil industry undergoes initial treatment through a combination of physical and chemical methods, followed by biological treatments. The physicochemical treatments encompass the use of coagulants, flocculants, adsorbents, and membrane filtration techniques. In this context, coagulants and flocculants alter the physical state of colloidal substances, leading to their destabilization and the formation of particles or flocs (Ahmed et al., 2015). This process reduces the load of colloidal and suspended particles in the effluent and aids in the reduction of organic compounds. Commonly employed coagulants include aluminum chloride, aluminum sulfate (alum), polyaluminum chloride (PAC), hydrated lime, and ferrous sulfate (Ahmad et al., 2019).

Adsorption is another effective physicochemical method for treating wastewater from the edible oil industry. Adsorption occurs when the attractive forces on the surface of an adsorbent overcome the attractive forces of dissolved substances present in the liquid (Qasim & Mane, 2013). Through this interaction, unwanted substances bind to the adsorbent material, such as chitosan, activated carbon, and zeolite, and are subsequently removed from the system. Adsorption is particularly efficient in removing oil, grease, and heavy metals from wastewater (Iskandar et al., 2018).

In recent times, membrane treatment, including membrane separation and filtration, has gained attention due to its capacity to remove a significant volume of chemicals and microbes from wastewater (Iskandar et al., 2018). Nevertheless, membrane treatment is challenged by fouling, which reduces membrane performance over time and shortens the membrane's lifespan (Pulido, 2016). To mitigate this issue, pretreatment of the feed (Gholamzadeh et al., 2016) and modification of the membrane surface properties to enhance hydrophilicity (Iskandar et al., 2018) can be employed.

On the other hand, biological treatments are essential for reducing or eliminating emulsified grease, which is the end product of physicochemical treatment. If left untreated, emulsified grease can lead to blockages in sewer pipes and pumps (Kalat & Yüceer, 2017). These biological methods are favored for their simplicity and cost-effectiveness. Based on their oxygen requirements, biological treatments are categorized into aerobic and anaerobic treatments, which can be used individually or in combination (Abdollahzadeh Sharghi et al., 2016).

Beverage Industry

The beverage sector plays a key role in producing a wide range of beverages and ready-to-drink items, such as bottled water, energy drinks, carbonated beverages, coffee, dairy products, various alcoholic beverages, and nutritional drinks. In 2021, the global beverage industry was worth $24.42 billion, and it is expected to expand significantly, reaching $71.83 billion by 2030, with a compound annual growth rate (CAGR) of 12.7%, as projected by SkyQuest Technology Consulting Pvt. Ltd. in 2022.

Producing beverages involves using a substantial amount of fresh water, resulting in the generation of significant volumes of wastewater throughout various stages of the manufacturing process. Common uses of water include the liquid components of the beverages, water used for cooling, bottle washing and disinfection, cleaning of workspaces and floors, and washdown procedures. Among these various processes, water cooling stands out as the most significant contributor to water consumption in a beverage factory. It accounts for approximately 59.5% of the total water used in the production process, as reported by TSI in 2010 (as cited in Bailone et al., 2022).

CASE STUDY 4: Water Footprint Assessment of Red Wine produced by a Medium-sized Umbrian Winery (Bonamente et al., 2015)

The case study utilized a Life Cycle Analysis (LCA) approach, encompassing the entire journey of the 750 mL wine bottle from grape cultivation to the final product end-of-life of life. This approach comprehensively considers all water volumes involved, whether they are physically present or virtually connected, including water withdrawn and later returned to the environment at different times or locations. For instance, this includes factors like rainwater evapotranspiration and runoff from irrigation practices.

The study's findings demonstrated that the total water usage associated with the production of a 750 mL wine bottle amounts to 632.2 liters. The primary contributor to this water usage is the green water footprint, accounting for a dominant 98.3%, while the grey and blue water footprints make up smaller portions at 1.2% and 0.5%, respectively.

To reduce water usage, minimize environmental impacts, and cut the substantial costs associated with water and wastewater management in the food and beverage industry, a range of water recycling and reuse methods have been put into practice.

In a study conducted by (Alkaya & Demirer, 2015), a fruit concentrate and fruit juice company successfully reduced its cooling water consumption by 95.2%. It is achieved by replacing once-through cooling systems with closed-circuit cooling systems for their production lines. Simultaneously, reusing the cooling water blow-down from the fruit washing process was recommended. This approach has proven effective not only in the food and beverage sector but also in other manufacturing industries.

In another case, a mandarin orange canning company installed a water reclamation system that employed chlorination, active carbon filtration, and UV sterilization. This system allowed the company to reuse treated water for tasks like segmenting, transporting, and fruit washing, resulting in substantial water savings (Wu et al., 2013).

In Australia, a non-alcoholic drink and cordial producer plant conducted a water audit followed by water pinch analysis to identify opportunities for water reuse. This analysis led to the realization of recycling options, resulting in daily water savings of 83.2 cubic meters and a wastewater reduction of 8.6% (Agana et al., 2013).

2. Water-related Challenges in the Food Industry

As previously discussed, various segments within the food industry are contributing to water stress through their substantial water use and the production of wastewater. Conversely, the industry is also confronted with water-related issues as it strives to meet the demands of a growing population. With this in mind, we will now delve into these challenges to acquire a comprehensive grasp of their ramifications and possible outcomes.

2.1. Water scarcity

Water scarcity, which occurs when the need for water surpasses the available supply, is a worldwide issue. The food industry depends significantly on a reliable and sufficient water supply for its various processes. The intense competition for water resources among different sectors presents a notable challenge. This heightened competition can diminish the accessible water resources for food processing activities, potentially leading to a decrease in processing capacity and a slowdown in production rates, ultimately affecting the total food product output. Additionally, it can result in elevated food prices due to increased operational costs.

2.2. Water quality and contamination

The quality of water employed in food manufacturing and processing plays a crucial role in determining the quality and safety of the food. Ensuring that the water utilized is of exceptionally high quality is imperative to produce wholesome and sanitary food. When water becomes compromised due to direct contamination or insufficient water treatment procedures, it often leads to the contamination of food products, posing a risk to human health.

2.3. Wastewater management

Wastewater management in the food industry can be challenging due to several factors, including the nature of food processing and the environmental regulations in place. Some of the key challenges in wastewater management for the food industry include:

VARIABILITY IN WASTEWATER COMPOSITION

Food processing encompasses a wide range of products, from dairy to meat processing, fruit and vegetable canning, and edible oil production. Each of these processes generates wastewater with different chemical constituents. For instance, dairy wastewater may contain high levels of lactose, while meat processing wastewater may have elevated levels of proteins and fats. This variability makes it challenging to design a one-size-fits-all wastewater treatment system. Therefore, customized treatment solutions are often required to effectively manage the different types of wastewaters.

HIGH ORGANIC LOAD

The presence of high concentrations of organic matter, such as fats, oils, and proteins, in food processing wastewater can be problematic (Pervez et al., 2021). These organic compounds can lead to issues like high biological oxygen demand (BOD) and chemical oxygen demand (COD), which, if not treated properly, can harm aquatic ecosystems when discharged into natural water bodies. Specialized treatment processes, like activated sludge systems, anaerobic digestion, or chemical coagulation, are often necessary to address this challenge.

SEASONAL VARIATIONS

Some food processing operations are seasonal. For example, fruit and vegetable processing may be concentrated during harvest periods. These seasonal variations in production can lead to fluctuations in wastewater volume and composition, which wastewater treatment facilities must be prepared to handle efficiently to avoid overloading or underutilizing their treatment capacity.

ODOR AND AESTHETIC CONCERNS

Food processing wastewater can produce unpleasant odors and discolored water. This can lead to aesthetic concerns for local communities and potentially impact public perception. Effective odor control measures and visual mitigation strategies may be needed to address these concerns.

AGING INFRASTRUCTURE

Many food processing facilities have wastewater treatment infrastructure that may be outdated or in need of maintenance and upgrades. These aging systems can be less efficient and may not meet current regulatory standards. Retrofitting or replacing these systems can be costly but is often necessary to meet modern environmental standards.

2.4. Energy consumption and water use

Energy-intensive water treatment processes such as purification, filtration, and disinfection, contribute to higher operational costs and environmental impact. Balancing water treatment efficiency with energy consumption is a challenge for the food industry.

2.5. Compliance with regulations

The food industry consistently faces the ongoing challenge of adhering to evolving water-related regulations and standards. These regulations encompass areas like discharge limits, water consumption, and wastewater treatment. They are dynamic, subject to modification over time as governmental bodies, environmental agencies, and industry associations strive to address emerging concerns related to water quality, conservation, and environmental safeguarding. These modifications may involve revising discharge thresholds, imposing restrictions on water usage, and enhancing requirements for wastewater treatment. Keeping pace with these evolving regulations demands allocation of resources.

Furthermore, certain regulations, which are specifically designed to safeguard water resources and ecosystems, set forth stringent criteria and benchmarks aimed at preventing contamination, curbing water consumption, and ensuring responsible handling of wastewater. Achieving these objectives often requires significant investments in advanced technology and robust infrastructure, making compliance a resource-intensive endeavor.

2.6. Public awareness and consumer demand

Consumers are becoming more aware of environmental and sustainability issues, including those related to water usage (Malochleb, 2018). This heightened awareness means that consumers are now more mindful of the environmental consequences of their buying choices. Consequently, they are more likely to favor products and companies that share their values, especially when it comes to using water responsibly. For industries like food and beverages, meeting these consumer expectations for environmentally responsible water use is a significant challenge.

2.7. Water footprint assessment

The evaluation of water footprints is essential for crafting strategies for water allocation, devising water trading plans, shaping policies, and enacting corrective actions (Mehla et al., 2023). Particularly within the food industry, assessing the water footprint of food products is essential for promoting sustainable water management and making informed decisions about production and consumption. It helps identify opportunities to reduce water usage, improve supply chain efficiency, and minimize environmental impacts. Nevertheless, comprehending and appraising the water footprint of food products across their entire life cycle poses a complex challenge. This process involves quantifying and analyzing the total amount of water consumed or affected by a product from its initial stages of production, such as agriculture, through processing, and even during transportation.

Addressing these challenges requires a multi-faceted approach involving sustainable practices, technological advancements, stakeholder collaboration, policy frameworks, and consumer education and engagement.

3. Strategies to Reduce Water Footprint in the Food Industry

Reducing water footprint in the food industry is essential for both environmental sustainability and resource efficiency. Water is a limited resource, and its conservation is critical to ensure long-term food security. Here are some strategies that the food industry can implement to reduce its water footprint:

3.1. Efficient water use in processing

There are several ways on how to achieve water use efficiency in food processing plants. The following are strategies and practices for achieving water use efficiency in food processing plants, with a focus on process controls and related methods:

UPGRADING PROCESSING FACILITIES WITH WATER-EFFICIENT EQUIPMENT AND TECHNOLOGIES

The heart of achieving water use efficiency in food processing begins with modernizing equipment. This includes installing water-efficient machinery, such as high-pressure, low-flow nozzles for cleaning and sanitizing. Replacing older, water-intensive equipment with newer, more efficient models can result in substantial water savings over time.

REGULAR MAINTENANCE AND CALIBRATION

Ongoing maintenance and calibration of equipment are crucial. Properly maintained machinery is less likely to develop leaks, which can waste significant amounts of water. Routine inspections and maintenance schedules help identify and address issues promptly.

OPTIMIZING PROCESSING METHODS FOR WATER EFFICIENCY

Customizing processing methods for specific products is essential to minimize water use while maintaining product quality. This optimization can involve adjusting cooking times, temperatures, or other factors. Employing best practices like blanching or steaming instead of boiling, as these methods generally require less water, is another way to reduce water consumption.

TRANSITIONING TO CONTINUOUS MANUFACTURING

Shifting from batch operations to continuous manufacturing processes can significantly reduce water consumption. Continuous processes often require less frequent cleaning and result in fewer interruptions for equipment sanitization. Also, improved production scheduling and product changeover procedures can reduce or eliminate the need for frequent cleaning between product runs.

OPTIMIZING CLEAN-IN-PLACE (CIP) SYSTEMS

CIP systems are essential for cleaning and sanitizing food-processing equipment and spaces. Optimizing these systems can lead to substantial water savings. Moreover, automation and monitoring of CIP systems ensure that cleaning is thorough and efficient while using the minimum amount of water necessary.

STRICT CLEANING AND SANITIZATION PROTOCOLS

Developing and following strict cleaning and sanitization protocols is paramount. These protocols should aim to minimize water wastage while upholding high hygiene standards. Providing employees with training in effective cleaning methods and the correct utilization of cleaning equipment is crucial to ensure that water is utilized efficiently and not squandered during the cleaning procedure.

By implementing these strategies and practices, food processing plants can make significant strides in achieving water use efficiency. These efforts not only reduce operational costs but also contribute to environmental sustainability by conserving a precious resource and demonstrating corporate responsibility in water stewardship.

3.2. Wastewater Treatment and Reuse

Water reuse systems have gained increasing attention and are seen as promising technologies in the context of sustainability. In many cases, wastewater discharged from food processing plants can be treated using innovative and advanced methods, allowing it to be reused. However, the specific approach to water reuse should consider several factors, including quantitative aspects (the volume of wastewater generated), chemical characteristics of pollutants (such as oils), physical-chemical parameters (e.g., biological oxygen demand, solid or liquid pollutants), and how these characteristics may vary over time (Barbera & Gurnari, 2018).

Different strategies and systems are available for the food industry to implement water reuse effectively. The choice of the right strategy depends on various factors, including the results of chemical and biological tests conducted on the initial wastewater and the intended final use of the treated water. Additionally, the nature of the chemicals and contaminants present in the wastewater may influence the selection of the most appropriate treatment methods. In some cases, treated wastewater may not be suitable for direct use in food processing but can still find valuable applications in non-food industrial processes, such as cooling or cleaning.

3.3. Supply Chain Optimization

The information provided by FAO (2013) highlights the staggering magnitude of global food wastage. According to their estimates, a vast 1.6 billion tons of "primary product equivalents" are wasted each year, with 1.3 billion tons of this representing the edible portion of food. This not only signifies a significant loss of food resources but also has a profound impact on water usage in food production.

To put this into perspective, the annual volume of water used to produce food that ultimately goes to waste amounts to 250 cubic kilometers (km^3). This is an astounding quantity, equivalent to the annual flow of Russia's massive Volga River or three times the volume of Lake Geneva, one of Europe's largest lakes. Such a substantial water footprint associated with food wastage underscores the urgency of addressing this issue.

Reducing food waste along the supply chain becomes imperative not only for conserving food resources but also for minimizing the immense water resources used in its production. To tackle this challenge effectively, it is crucial to identify and address weak points in the supply chain where wastage occurs. This may involve improving storage and transportation infrastructure and implementing better inventory management systems.

3.4. Investing in Research and Innovation

Supporting research and development efforts to create water-efficient processing technologies is a commendable initiative to reduce water footprint. It may include investing in new food processing techniques that require minimal water use such as high-pressure processing, pulsed electric field processing, or microwave heating.

3.5. Collaboration and Partnerships

Collaboration with stakeholders and participation in industry initiatives are vital for comprehensive water sustainability in the food industry. These efforts not only help individual companies reduce water usage but also contribute to broader goals like conserving water resources, protecting ecosystems, and ensuring clean water availability. This includes partnering with water management organizations to promote responsible water use, engaging with local communities to assess and improve water impacts, and collaborating with environmental Non-Government Organizations (NGOs) to support water conservation and sustainability initiatives. Overall, such collaboration enhances both corporate responsibility and environmental stewardship within the food industry.

Reducing the water footprint in the food industry is a multifaceted challenge that requires collaboration among all stakeholders, from farmers and processors to consumers and policymakers. Implementing a combination of these strategies can help minimize water usage while ensuring sustainable food production and supply.

4. Conclusions

Water plays a vital role in the food industry, serving as a crucial ingredient in food production and various processing activities. The food industry encompasses diverse sectors such as meat, fish, dairy, fruits and vegetables, beverages, and edible oil, each with specific water requirements to produce high-quality products that meet consumer needs. Primarily, water is predominantly used for sanitation purposes. In addition, the food industry generates substantial wastewater, posing a significant risk to the environment and finite natural resources.

To address these challenges, different sectors within the food industry are actively seeking ways to reduce water consumption through methods like recycling treated wastewater, practical strategies, technological advancements, and process optimization. However, the industry faces hurdles in the form of declining water quality and quantity, stemming from the growing global population's increasing demands. Complying with regulations, meeting consumer expectations, and implementing responsible water management are ongoing challenges for the food industry.

In summary, the relationship between water and the food industry is intricate. Collaboration between the food industry, governmental bodies, non-government agencies, and the public is essential to achieve water sustainability. Successfully reaching this goal can lead to a more secure food supply for the growing population.

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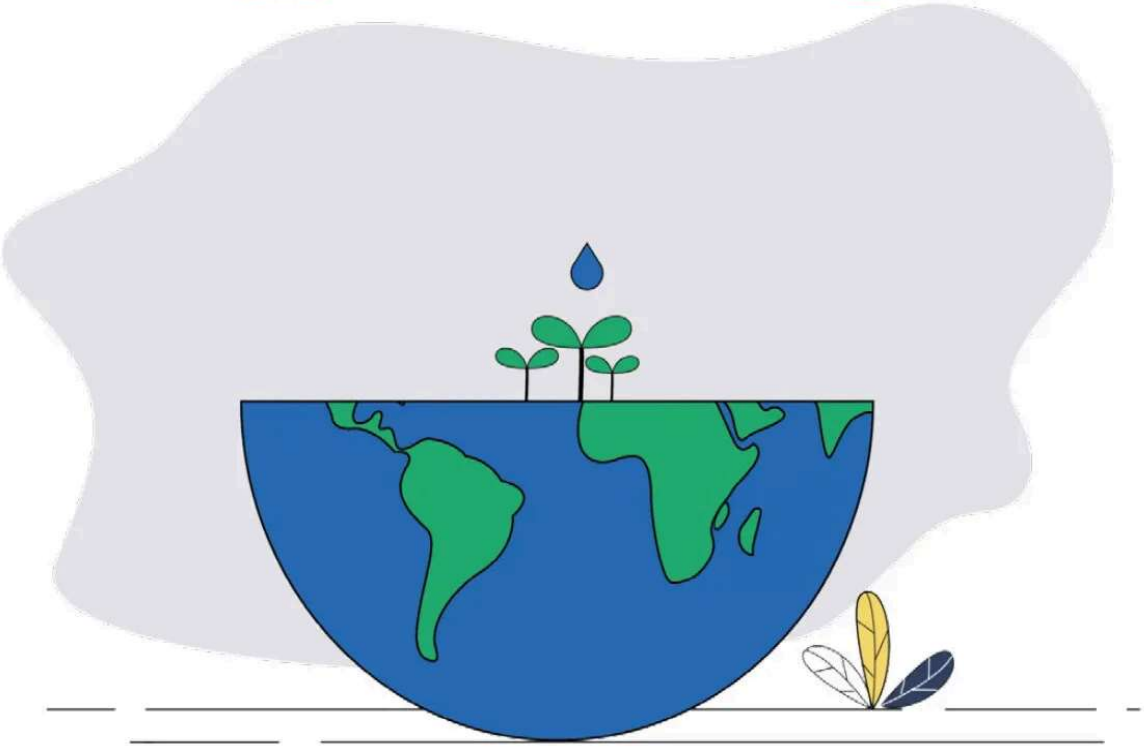
5. VULNERABLE GROUPS

Closing the WEF insecurity gap for vulnerable rural populations through nexus planning in global South: a case study of Matabeleland South Province, Zimbabwe



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1. Introduction

Climate variability and change, coupled with the increasing populations, are driving increased demand for freshwater resources, consequently and continuously widening the gap between the "haves" and the 'have nots". This has threatened climate-sensitive sectors; this was compounded by COVID-19 challenges. Confounding factors like the COVID-19 pandemic and the war in Ukraine have also worsened vulnerabilities in the global South, as shown by supply disruptions and high inflation rates driving food and energy commodity prices.

The war between Ukraine and Russia affects most countries that heavily depend on these two countries, especially for food and energy in sub-Saharan Africa. In this context, vulnerable groups may be unable to meet their basic needs and are at risk today of being in poverty or falling into deeper poverty in the future, with a diminished capacity to anticipate, cope with, resist and recover from the impact of natural or man-made hazards (UNHCR, 2006; Mechanic and Tanner, 2007; Vink and Takeuchi, 2013; Lazarte, 2017; Kuran et al., 2020). According to UNDESA (2020), vulnerable groups are defined by their geographic location (isolated, insecure, defenseless), way of life (poverty), heavy reliance on climate-sensitive natural resources or assets for their livelihoods, and they include smallholder farmers, indigenous peoples, and rural populations (Dasgupta et al., 2014).

The proportion of rural people in extreme poverty is rising in sub-Saharan Africa (SSA) (Dasgupta et al., 2014). Despite the promise of sustainable development to leave no one behind, disparities between rural and urban areas are glaring, with the former often lacking adequate infrastructure and services (UNDESA, 2020). For example, in South Africa, most people are migrating from rural to urban areas hoping to find job opportunities, better life and better services; this seriously impacts infrastructure in urban or metropolitan areas.

Vulnerable groups such as rural populations which constitute approximately 44% of global population still lag in access to and utilization of key resources for survival, compared to the urbanites. Five years after the adoption of the 2030 Agenda for Sustainable Development, the global urban population was leading the rural people in security of water, energy and food (WEF) resources and the situation was even worse in sub-Saharan Africa (SSA) in 2020 (UN, 2022a). This could be blamed on historic, traditional, and current conventional development approaches that prioritise specific sectors, geographical locations and people allocating resources at the expense of leaving others behind. This is contradictory to the basic tenets of interconnectedness and indivisibility of Sustainable Development Goals (SDGs); and a violation of the 2030 Agenda for Sustainable Development's pledge to ensure "no one will be left behind" and to "endeavour to reach the furthest behind first" (UNGA, 2015).

Inclusive and innovative approaches and tools can be applied to understand the complex socio-economic dynamics and design context-specific interventions for identified vulnerable groups. For example, the water-energy-food (WEF) nexus allows for optimizing interlinkages amongst the interconnected and complex natural resources for sustainable resource utilisation and potential just transition for redress. Mabhaudhi et al. (2019) argued that if adopted at a higher level, the WEF nexus can substantially improve livelihoods in resource-poor communities by mitigating unintended trade-offs.

Vats et al. (2021) highlighted the versatility of the WEF nexus approach by coupling it with Leontief's production functions to inform policy on redressing WEF resource challenges in India. Dlamini et al. (2023) applied the WEF nexus approach to design effective interventions to support multiple water use (MWU) in the Buffalo River catchment of South Africa. Another case study by Dlamini et al. (2023) quantified WEF nexus indices to assess the management of WEF nexus resources in South Africa. Thus, nexus approaches such as water-energy-food (WEF) acknowledge that WEF sectors are interlinked, and their resources can be better managed and allocated by minimizing trade-offs, optimizing synergies and harmonizing resource needs and endowments (Nhamo et al., 2018).

Zimbabwe is party to several global, continental and regional commitments which envision universal access to WEF resources, including the Universal Declaration of Human Rights (General Assembly Resolution 217 A) (UNGA, 1948), Resolution A/RES/64/292 (UNGA, 2010), Resolution A/76/L.75 (UNGA, 2022), 2030 Agenda for Sustainable Development (UNGA, 2015), Agenda 2063 (The Africa We Want) (AUC, 2015), African Charter on Human and Peoples' Rights (AU, 1981), ACHPR Resolution 300[1] and ACHPR Resolution 431 (LXV) 2019[2]. In Zimbabwe, the security of WEF resources for all is enshrined in the Constitution of Zimbabwe (GoZ, 2021), and the country's policy framework, including Vision 2030 (GoZ, 2018), National Development Strategy 1 (NDS1, 2021-2025), National Water Policy (GoZ, 2012c), National Energy Policy (GoZ, 2012b) and Food and Nutrition Security Policy (GoZ, 2012a). Despite this, Zimbabwe is among the many countries challenged with extending services to rural areas, which usually have lower coverage of WEF services and resources than urban areas (UN, 2023).

Poverty, the COVID-19 pandemic, inequality and political and economic instability complicate the country's challenges related to WEF security. Some quarters partly attribute the ailing economy and its impacts on WEF insecurity to the economic sanctions embargoed by western countries since 2001 (ZIMFA, 2019; Mukonavanhu et al., 2021; Tirivangasi et al., 2023)[3]. An approximated 70.5% and 29.3% of the population were poor and extremely poor in 2017, respectively (ZimVAC and FNC, 2022c).

The country is highly unequal in terms of income, as indicated by its appearance in the global top 20 list for a high Gini index (50.3%), undermining its efforts for WEF security for all (UNEN and UN-DESA, 2020). Generally, low- and middle-income countries (LMIC) with a Gini index higher than 35% have a 33-percentage-point higher probability of experiencing severe food and, potentially, energy and food insecurity than countries with a lower Gini index (UNEN and UN-DESA, 2020).

Few WEF nexus studies were conducted in Zimbabwe, including for a river basin (Gomo et al., 2018; Koundouri and Papadaki, 2020), a multi-purpose dam (Mujere and Chanza, 2022) and a city (Gandidzanwa and Togo, 2022). Although useful, the operationalisation of the WEF nexus is fraught with challenges. There have been laggards in shifting from theory to practice. The reason being there are many variables that require convergence for the WEF nexus operationalisation. Such variables include convergence of ideas and reaching consensus on planning, governance, and adoption amongst multiple stakeholders. The intricacies involved are articulated by (Naidoo et al., 2021).

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The challenges mentioned above warrant research, and this study sought to provide solutions by applying the WEF nexus approach to (i) assess the disparities in access to WEF resources between the urban and the vulnerable rural populations, and (ii) identify and propose nexus solutions in the rural areas of Matabeleland South province of Zimbabwe.

2. WEF Nexus application: Case of Matabeleland South Province, Zimbabwe

2.1. Description of the study area

Matabeleland South Province is located in the southern part of Zimbabwe sharing boundaries with Botswana and South Africa, and covers a surface area of 54,172 km^2. The province has seven rural districts, namely Beitbridge Rural, Bulilima, Gwanda Rural, Insiza, Mangwe, Matobo, and Umzingwane; and three urban districts, Beitbridge Urban, Gwanda Urban, and Plumtree (Figure 1) (ZimStat, 2023b).

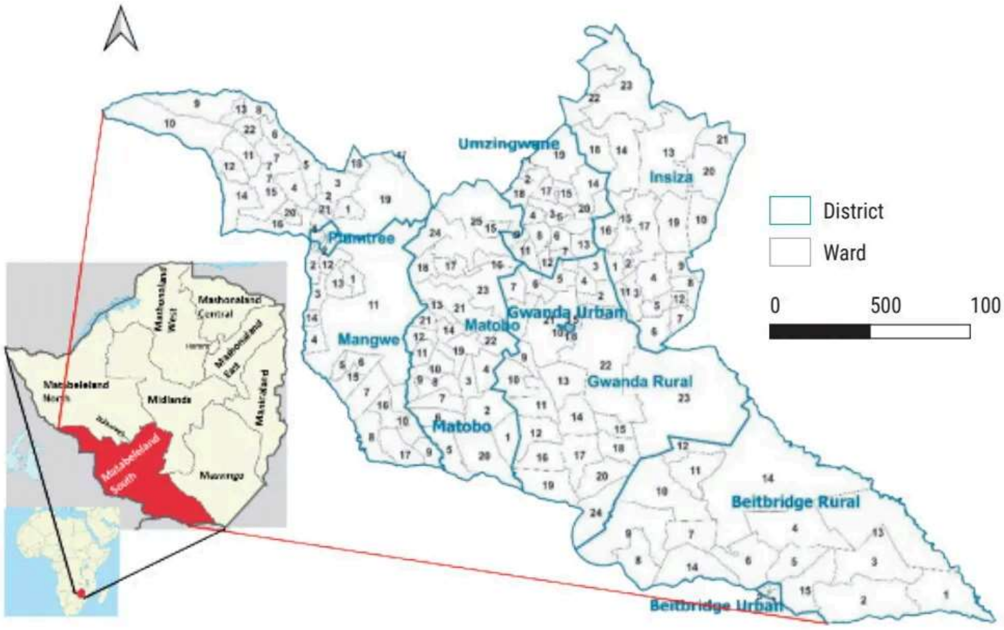

Figure 1: Map of Matabeleland South Province and its districts and wards (ZimStat, 2023b)[4]

The province has a total population of 760,345 people, and 193,328 households are mainly rural (86.8%), with an average household size of 3.9 people (ZimStat, 2023b). Matabeleland South Province has a naturally arid to semi-arid climate (Duker et al., 2020), spanning over three revised agro-ecological zones (AEZs), mainly IV and V (Va and Vb), and partly III. The province receives mean annual rainfall (erratic) ranging from 400 mm to 800 mm/year, with maximum temperatures ranging from 25°C to 32°C. Among other challenges, the province is generally a water-scarce province, which makes it more suitable for rainfed production of short-season maize varieties and drought-tolerant crops such as sorghum, finger millet, pearl millet, watermelons and cowpeas (Figure 2).

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[4] https://en.wikipedia.org/wiki/Matabeleland_South_Province; https://en.wikipedia.org/wiki/File:Zimbabwe_in_Africa_(-mini_map_-rivers).svg

Figure 2: Dry beds of river (a) at Pendi river, and dams in (b) Esibomvu, and (c) Mashaba; (d) land degradation at Mashaba; (e) illegal mining in Gwanda; and siltation in (f) Tuli and (g) Mashaba.

Extensive cattle ranching, rearing of small stock (e.g., goats and poultry) and wildlife are ideal farming systems for this region (Manatsa et al., 2020). The province hosts interesting tourist sites and is endowed with precious minerals, including gold. It is also home to the mopani worms (amacimbi/madora), a local and regional delicacy (GoZ, n.d.).

The provincial capital is Gwanda town, while Beitbridge is the province's largest town. The province's economy is mainly based on mining and agriculture (subsistence, commercial, livestock). Poverty and migration are widespread due to droughts and a lack of economic opportunities (GoZ, n.d.). The main source of energy is biomass which is resulting in massive deforestation. Most households (57.6%) do not have access to either grid or off-grid electricity besides the huge potential for solar energy (ZimStat, 2023a).

2.2. Data sources

For the rural and urban areas, data for water, energy, and food security was considered for the year 2021 from different sources, including literature and reports by government agencies such as Zimbabwe Vulnerability Assessment Committee (ZimVAC) and Food and Nutrition Council (FNC) (ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022b; ZimVAC and FNC, 2022a), and Zimbabwe National Statistics Agency (ZimStat) (ZimStat, 2023a; ZimStat, 2023b). The data comprised a total of six indicators on the security of water, energy, and food resources (Table 1).

Table 1: Pillars and indicators of water, energy and food security.

Pillar	Indicator	Definition
Water security	Access to improved water (%)	The proportion of population/households who have access to water sources that are protected from faecal contamination, including piped water, tap/standpipe, tube well/borehole, protected well / spring, rainwater, packaged and delivered water
	Access to improved sanitation (%)	The proportion of population/households with access to facilities that ensure hygienic separation of human excreta from human contact, including flush or pour-flush toilet/ latrine, Blair ventilated improved pit (BVIP), pit latrine with slab and upgradeable Blair latrine.
Energy security	Access to grid electricity (%)	The proportion of population/households connected to the national and local electricity mini-grids.
	Access to clean energy for lighting and cooking (%)	The proportion of population/households who use clean energy sources for lighting and cooking, including electricity, biogas, liquefied petroleum gas (LPG), alcohol/ethanol, solar lanterns, battery-powered flashlights, cell phone flashlights, and torches
Food security	Food consumption score (%)	The proportion of population/households who consumed an acceptable and borderline balanced diet, including staples, vegetables, sugar, oil/fat, animal proteins, and dairy products
	Food security (%)	The proportion of population/households who were able to meet the minimum food energy requirements

Sources: (ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022b; ZimVAC and FNC, 2022a)

2.3. WEF nexus analytic tool – Sustainability polygon

Sustainability polygons are a simple and yet powerful tool to visualize and evaluate multiple indicators and their interconnections. For normalisation, each indicator is scaled between 0 (least desirable) and 1 (or 100, most desirable), based on the value range of assessed alternatives, and is represented on an axis with 0 at the centre of the plot and 1 (or 100) at the outside border.

The indicator scores of each alternative are connected with lines to form polygons. If one polygon completely encloses another, it means that the corresponding option is more sustainable; and if polygon borders overlap, an alternative criterion can be used, i.e., the comparison of the polygon area. The option with the greater polygon area is considered more sustainable (FAO, 2021b). Sustainability polygons have been successfully applied in understanding and highlighting synergies and trade-offs in interlinked systems (FAO, 2021a; Taguta et al., 2022).

Since the same polarity was maintained for all indicators, i.e., desirability of a higher score, and their scale (0 – 100) and units (%) were similar, there was no need for further normalization, and logically the area of the sustainability polygon/radar chart/spider diagram is a proxy measure for the performance of the integrated system. Thus, the area of the sustainability polygon was used as the integrated WEF nexus composite index (see Equation 1):

$$WEF_{index} = SP_{area}$$

Equation 1

where: WEF_{index} is the integrated WEF nexus composite index equating to SP_{area}, the area of the sustainability polygon in unit^2, which in this case is a combination of irregular triangles with known two sides and angle (in this case 60°) between them.

3. Findings or Outcomes

The sustainability polygon for the urban areas in Matabeleland South Province was bigger and more circular than that for the rural areas, the area of the former enclosed and was more than half of that for the latter (Figure 3).

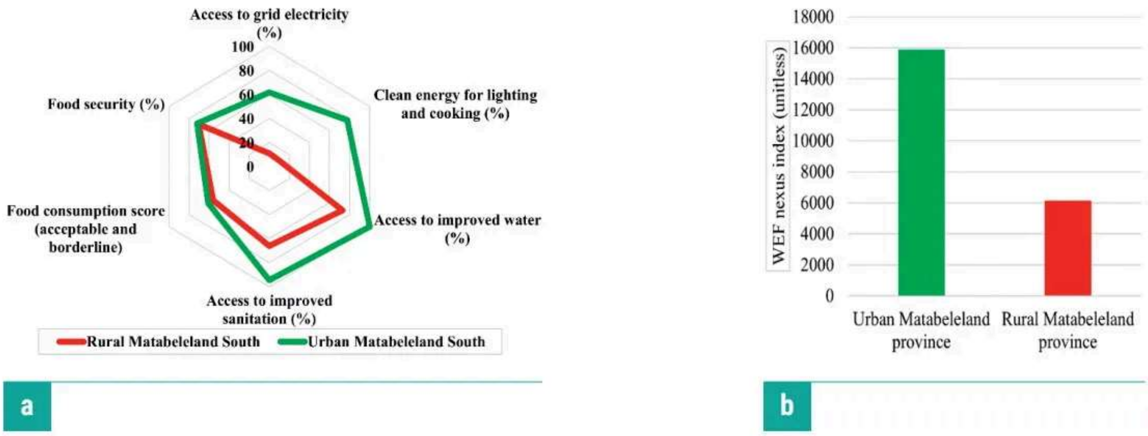

Figure 3: The rural-urban divide in WEF nexus security (a) sustainability polygons and (b) WEF nexus indices for rural and urban Matabeleland South Province.

Thus, from an integrative WEF nexus perspective, the urban areas surpass the rural areas in balanced WEF resources management and security. The rural areas are insecure for water, energy and food compared to the urban areas, and their integrative WEF nexus performance is way lower (more than half) than that of urban areas (Figure 3b).

The urban areas have a universal and higher access (100%) to improved water supply and services than rural areas (73%) (Figure 3a). Due to lack of access to the government network of water supply, rural areas tend to directly use water from unimproved surface sources which they treat mainly by boiling, chlorination, settling/standing, filtering, and straining (ZimVAC and FNC, 2022c). Compared to the urban areas, the rural people travelled a longer distance to a water source, spend more time queuing at a water source, and experience more violence at a water source (ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022a).

Despite their universal access, some urban households (28%) complained of poor and unreliable services from the water supplier, either Zimbabwe National Water Authority (ZINWA) or Council (ZimVAC and FNC, 2022a). Only 22% of the urbanites were satisfied with water provision service (e.g., water cuts), while 42% were satisfied with the quality of water provided and some urban households (13%) had to treat their household drinking water (ZimVAC and FNC, 2022a).

The rural areas underperform (66%) in access to improved sanitation than urban areas (94.5%) (Figure 3a) (ZimVAC and FNC, 2022c). About a third of the rural households practise open defecation with potential for surface and groundwater pollution (ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022b; ZimVAC and FNC, 2022a; ZimStat, 2023a). The state of water security in the province can be partly attributed to the poor state of water infrastructure. For example, the province hosts a diversity of water sources including boreholes and dams which are at different functional status (Figure 4).

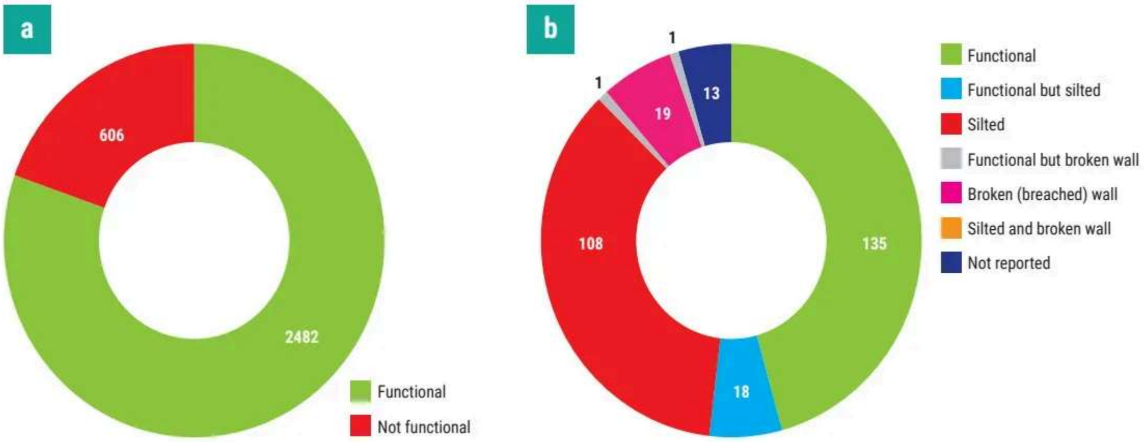

Figure 4: Functional status of water sources in Matabeleland Province (a) boreholes by number, and (b) dams (GoZ, 2022b; GoZ, 2022d; GoZ, 2022e; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i).

Approximately 20% of the boreholes are not functional due to insufficient funds, collapsed rods/pipes, failure of community-based maintenance, shortage of spare parts, hydrological droughts, vandalism, incorrectly sited boreholes, and shifting and receding water tables (drying up) (GoZ, 2022e; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i). On the other hand, the functionality of small, medium and large dams is compromised by siltation, wall breaching, and leaking (GoZ, 2022b; GoZ, 2022d; GoZ, 2022e; GoZ, 2022f; GoZ, 2022g).

The rural areas (11.0%) trailed the urban areas (61.7%) in access to grid (national and mini) electricity (Figure 3a). Despite their connectivity to electricity networks, urban people suffered acute energy insecurity due to load shedding. The urban areas (77.5%) outperformed the rural areas (9.85%) in access and use of clean energy for cooking and lighting (Figure 3a). For example, approximately 80% of households in the province are not connected to the government and mini-grids of electricity (ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022b; ZimVAC and FNC, 2022a; ZimStat, 2023a). This group contains 90% of rural inhabitants and such dirty and polluting fuels like firewood are the likely cause of air pollution induced ill health and 800000 to 1.1 million deaths per year globally (Craig et al., 2022; SE4ALL, 2023) .

The urban areas (72%) had slightly higher proportion of people who were food secure than the rural areas (70.3%) who faced food insecurity challenges during the peak hunger season (January-March 2023) (Figure 3a). More households in the urban areas (61%) had acceptable and borderline food consumption score and balanced diets than in the rural areas (56%) (Figure 2a). These relatively moderate and almost similar performances in food security can be attributed to the involvement of both rural and urban areas in agriculture to produce staples (cereals), legumes, tubers, vegetables and fruits.

Around 12% of urban households were involved in urban agriculture (ZimVAC and FNC, 2022a). Similarly, many rural (70%) and some urban (24%) households received food support and assistance from government and partners (ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022a). However, a gap still exists to reach the National Development Strategy 1 (NDS1, 2021-2025) commitments of increasing food self-sufficiency to 100% and reducing food insecurity to less than 10% by 2025 (ZimVAC and FNC, 2022c).

Factors that could have undermined food security in the rural areas include a poor rain season characterised by a false start, poor distribution, a prolonged dry spell (drought), passage of Tropical Storm Ana, water logging and leaching (ZimVAC and FNC, 2022c). Other reported shocks in rural areas included steep increases in cereal prices, human wildlife conflict, sharp drop in livestock prices, and crop pests. Contributing factors in the urban areas include widespread poverty, cash-based nature of urban livelihoods, an unstable economic environment, a reduction of viable employment opportunities, climate-related shocks, food price increases, the COVID-19 pandemic and the measures taken to curb the pandemic such as lockdowns (ZimVAC and FNC, 2022a).

Food insecurity can partly be attributed to the suboptimal performance of irrigation schemes in the province. Matabeleland South province hosts an estimated 116 irrigation schemes of approximately 5574 ha and an additional 20 irrigation schemes are in planning phase with a threefold area of 17835 ha (Figure 5).

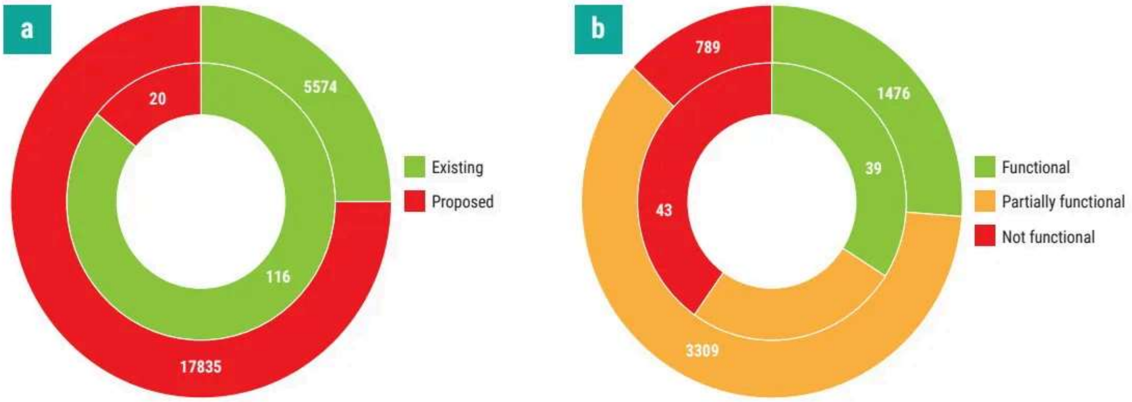

Figure 5: Irrigation schemes (a) planned and existing in Matabeleland South province, (b) and their functional status (Inner core: by number; Outer core: by area, ha). (GoZ, 2022b; GoZ, 2022d; GoZ,

2022e; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i)

The current provincial functional status of irrigation schemes is low at 34% by number of irrigation schemes or 26% by irrigated area (Figure 5b). The functionality of irrigation schemes is being undermined by water and electricity challenges, dysfunctional infrastructure and equipment (e.g., pumps, engines, pipes, canals, transformer, fences), vandalism, theft, breach and siltation of water sources, and human-animal conflict (GoZ, 2022b; GoZ, 2022e; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i). The water sources for existing irrigation schemes include surface and groundwater, with the former dominating (Figure 6a); while electricity is the major source of energy for the irrigation schemes (Figure 6b).

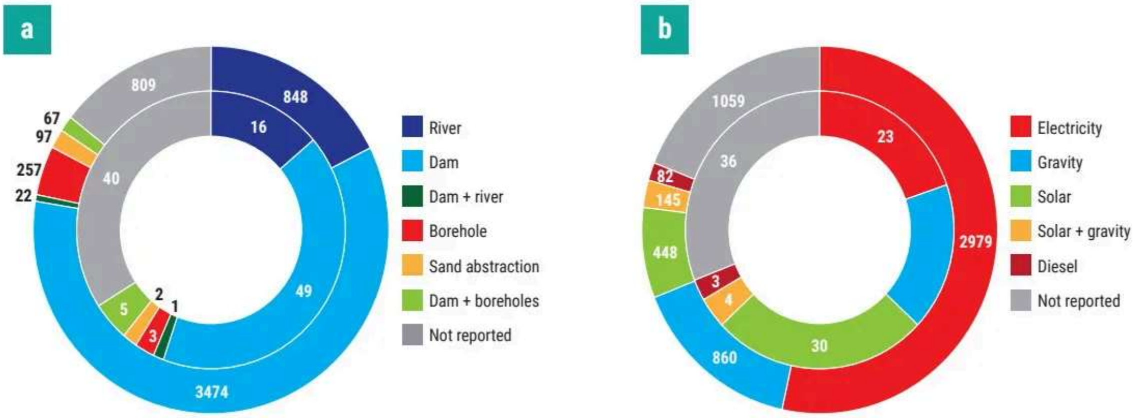

Figure 6: Sources of (a) water and (b) energy for irrigation schemes in Matabeleland South province. (Inner core: by number; Outer core: by area, ha) (GoZ, 2022b; GoZ, 2022d; GoZ, 2022e; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i).

The heavy dependence of irrigated agriculture on surface water and electricity is undermining production due to the persistent droughts and energy crisis. Irrigated area under flood systems is dominant over other irrigation technologies (Figure 7).

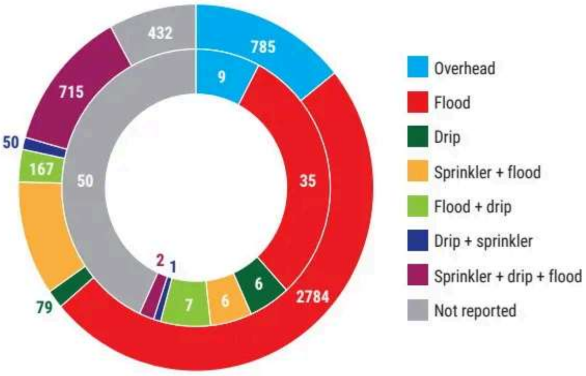

Figure 7: System technology for irrigation schemes in Matabeleland South province. (Inner core: by number; Outer core: by area, ha) (GoZ, 2022b; GoZ, 2022d; GoZ, 2022e; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i).

The high performance in the water and food sectors relative to the energy sector in the province's rural areas can be attributed to the biased support received in the former two sectors from the government and its partners. This support included food assistance (in-kind, cash transfers), food subsidies, removal of restrictions on food importation, agricultural inputs (seed, fertiliser, herbicides), and water infrastructure (dams, boreholes) (ZimVAC and FNC, 2022c). For example, the proportions of government support to rural households towards crop inputs, food, and cash were 46%, 45%, and 3%, respectively.

For support from United Nations (UN) and non-governmental organisations (NGOs) in rural areas, food dominated (60%), followed by crop inputs (26%), small livestock (4%), and cash (3%). Going forward, the government and its partners need to balance and equally consider energy security in dedicated support. To sum up, a need exists to close the gap in WEF nexus performance in rural areas for sustainable development that leaves no-one behind.

4. Lessons and Messages Derived

4.1. Threats to WEF security for vulnerable groups in rural Matabeleland South Province

The majority of the rural population's livelihoods in Matabeleland South Province is mostly dependent on agriculture (both crops and livestock), and it is vulnerable to shocks that impact the security of WEF resources and livelihoods (ZimVAC and FNC, 2022c). The multiple threats include poverty, inequality, historic marginalisation, climatic and economic shocks, crop and livestock diseases, the "last mile" problem, and disruptions by pandemics and conflicts (Duker et al., 2020).

The climatic shocks include droughts and prolonged mid-season dry spells, floods, water logging, and hailstorms. Economic shocks include economic instability and sharp changes of cereals and livestock prices; while pandemics include COVID-19 and geopolitical conflicts include the Russia-Ukraine war (ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022b). The most important source of income for about 20% of the households is external remittances, followed by casual labour (17%). Their average household monthly income was USD55 in 2021 of which food expenditure constituted almost half (48%) compared to urban households who spent less (about 38%) of their income on food expenditure (ZimVAC and FNC, 2022c).

'Last mile' underserved populations such as those in rural Matabeleland South Province usually lack access to adequate WEF resources due to lack of connection to national/regional networks of resource supply such as the water network, electricity grid, and food supply corridors (Rabta et al., 2018; Faal et al., 2022). Several factors contribute to the lack of access to basic services, including economics (cost), physical distance, cultural or belief systems, values and prioritisation, geography (isolation, terrain), low population density and dispersed households, low energy demand, poverty (fiscal deficit, generation resources), poor or non-existent infrastructure (inaccessibility), and local society perspective (Massoud et al., 2009; Lahimer et al., 2013; Rabta et al., 2018; Faal et al., 2022). Hence such communities end up exploiting natural ecosystems for traditional resources to satisfy their water, energy and food demand (Lahimer et al., 2013). Deliberately targeted strategies for the poor and vulnerable promote protection of natural capital, located mostly in marginalised areas and subjected to serious depletion by the surrounding communities as they try to survive on the available resources (UNDESA, 2021)[5].

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[5] United Nations (UN). Rethinking rural development for achieving SDGs. https://sustainabledevelopment.un.org/index.php?page=view&type=20000&nr=7361&menu=2993

4.2. Opportunities for WEF security for vulnerable groups – Off-grid, in situ and decentralised solutions

Despite the looming challenges to WEF security for vulnerable groups in rural areas, everyone is entitled to unconditional access to secure water, energy and food resources and opportunities lie in use of decentralized and in situ technologies (Figure 8).

Figure 8: (a) Ongoing expansion of Esigodhini water treatment and supply system; (b) a private sector-funded community water supply scheme; (c) a sand dam at Tuli; (d) a sand dam water treatment and supply system at Ntepe; (e) ongoing construction of the Tuli-Moswa Manyange multi-purpose dam; (f) a dam supplying water at Mzinyathini irrigation scheme; (g, h) a solar-powered, drip-irrigated and organic manure fertilized community food and nutrition garden at Esibomvu; biogas digesters (i) supplying fuel for cooking and treated manure at a livestock farm and (j) energizing at Gwanda Agricultural Show; and solar power farms (k) in construction at Richaw site in Gwanda, (l) energising Mashaba community, (m) energising Blanket (Caledonia) Mine, (n) and in construction at Intratek site in Gwanda.

Potential interventions for improving water storage and availability for enhancing water security include desilting, maintenance and repair of the province's compromised dams (Figure 4). For water security, potential decentralised solutions include rainwater harvesting, community water supply schemes and use of groundwater through boreholes, protected wells and sand dams (alluvial aquifers) (Figure 8).

In Sub-Saharan Africa where the rural population is large but dispersed, groundwater is one of the few feasible and affordable ways to extend basic water access to un- and underserved rural populations (UN, 2022b). For example, the good quality unconfined groundwater in shallow sand river aquifers of Matabeleland South Province has significant potential for productive use such as domestic supply, livestock, fishponds and smallholder farming (Duker et al., 2020).

Water access in Matabeleland South Province can be improved by repairing and rehabilitating the 606 non-functional boreholes (Figure 4), and drilling more boreholes and establishing additional sand abstraction points along the alluvial river beds. In situ decentralised wastewater treatment technologies include riverbank filtration, bioremediation, constructed wetlands (lagoons), septic tank, and leach drains (Ho, 2005; Vymazal, 2010; Ahmed and Marhaba, 2017). For advancing the circular economy in rural areas, the treated wastewater can be reused, while up flow - anaerobic sludge blanket reactor (UASB) wastewater treatment systems can simultaneously treat the wastewater, and produce biogas and treated manure as a by-products (Lohani et al., 2015; Adhikari and Lohani, 2019), somehow similar to the biogas systems for decentralized wastewater treatment (BiogasDEWATS) (de Porres Lebofa and Huba, 2011) (Figure 8). The viability of using reclaimed water in agriculture is increasing especially in water scarce regions and needs to be explored in rural Matabeleland South Province (UN, 2023).

Despite its persistent lack of access to energy services among the majority rural people, the sub-Saharan Africa region has an outstanding potential in cheaper levelized cost renewable energy resources (Winklmaier and Bazan Santos, 2018; Winklmaier et al., 2020). With a country mean practical photovoltaic (PV) potential (PVOUT) of 4.75 kWh/kWp per day, Zimbabwe ranks 31st globally and is among the 70 countries with excellent conditions for solar PV energy where the long term PVOUT average exceeds 4.5 kWh/kWp per day (ESMAP, 2020).

PVOUT is the power output achievable by a typical configuration of the utility scale PV system and accounts for the theoretical potential, the air temperature affecting the system performance, the system configuration, shading and soiling, and topographic and land-use constraints (ESMAP, 2020). PVOUT is the specific yield which is the amount of power generated per unit of the installed PV capacity over the long-term, as measured in kilowatthours per installed kilowatt-peak of the system capacity (kWh/kWp) (ESMAP, 2020). The Bulilima and Mangwe districts in Matabeleland South are among the areas with highest solar potential (PVOUT) in the country, for both PV and concentrated solar power (CSP) (Figure 9).

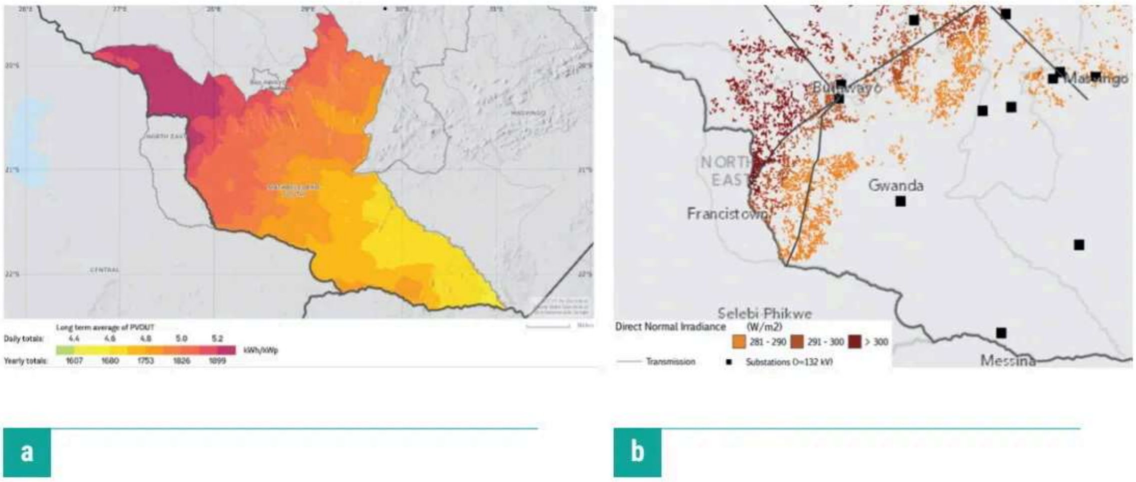

Figure 9: (a) PVOUT (ESMAP, 2020; Solargis, n.d.; Solargis and ESMAP, n.d.) and (b) concentrated solar power (CSP) potential and electricity transmission infrastructure Matabeleland South Province (IRENA and ZERA, 2019).

In the arid and hot Matabeleland South province, the daily PVOUT ranges from 4.46 kWh/kWp (1600 kWh/kWp per year) near Chikwarakwara and increases north-westwards to 5.18 kWh/kWp (1900 kWh/kWp per year) in Bulilima district (Solargis and ESMAP, n.d.). Fortunately, these areas possess the necessary electricity infrastructure such as substations and substations, what is lacking is the generation infrastructure (Figure 9b).

For energy supply, options include compartmentalised modular mini and micro-grids, bioenergy, and biogas digesters (Mang et al., 2013; IRENA and FAO, 2021) (Figure 8). For electrification and depending on energy demand and distance from the national grid, extending the national grid suits large or dense communities, mini-grids are suitable for mid-density communities, and stand-alone solar home systems are best for dispersed homes (Franz et al., 2014) (Figure 8).

Depending on setting and scale, types of biogas digesters include household-scale digesters, biogas septic tanks, and biogas plants for the treatment of municipal, industrial, and agricultural waste (Deng et al., 2017). A good example of a successful renewable minigrid in Matabeleland South province is the 99KW Mashaba Solar Minigrid which was established in 2016 and currently powers three irrigation schemes (Rustler's Gorge 31 ha, Mankonkoni 40 ha, and Sebasa 65 ha), and a school, clinic, and business centre (GoZ, 2022e; SNV, n.d.) (Figure 8). However, it must be borne in mind that some renewables (e.g., solar PV and onshore wind) have large land requirements which may lead to competition with agricultural production for food security (UNEP, 2017; IRENA and FAO, 2021).

Irrigation can potentially increase food production, reduce food prices, create rural employment, enhance overall agricultural and economic growth but it may also worsen farmer inequality and accelerate water depletion, degradation, and pollution (Ringler, 2021). Implementing the proposed and planned irrigation schemes of 17835ha will almost quadruple the irrigated area and potentially increase food security in Matabeleland South Province (Figure 5a). However, this will likely skyrocket the demand for water and energy resources in the water and energy food stressed province, unless additional water and energy resources are unlocked.

Generally depending on the state of partially- and non-functional irrigation schemes, their rehabilitation may be more cost effective than expanding and developing new irrigation schemes (FAO, 2003). A low hanging fruit in improving food security in the province is rehabilitating partially- and non-functional irrigation schemes which can potentially increase agricultural production.

Potential interventions may include system overhaul, repair of infrastructure and equipment, desilting water sources, and unlocking additional water and electricity sources, and fencing. Thus, any interventions in increasing the irrigated area need to be paralleled with sustainable development of ground and unconventional water. However, the pumping of groundwater and treatment of unconventional water will require additional energy supply.

Further irrigation development needs to consider alternative energy sources such as solar to derisk and decouple agricultural production from loadshedding and power cuts. Similarly, to save the scarce water, efforts for irrigation rehabilitation and expansion need to consider converting current irrigation systems towards modernised efficient irrigation technologies. However, it needs to be acknowledged that some water-saving irrigation technologies such as pressurised irrigation systems consume more energy than flood systems (Taguta et al., 2022).

As they rehabilitate and expand irrigation schemes, the government has piloted and is scaling the Vision 2030 Accelerator Model (V-30 Accelerator) which seeks to centralize rural communal irrigation schemes through the provision of a scheme business manager and changing farmers from plot owners to shareholders and workers (GoZ, 2022a). The scheme business manager provides all technical support, manages finances, facilitates profit sharing and ensures all debts are paid, to ensure the business, production, productivity and profitability (commercial viability and sustainability) of communal irrigation schemes, while ensuring national food self-sufficiency (GoZ, 2022c).

However, past experiences have shown that decentralised irrigation schemes such as through farmer-led irrigation (FLID) are more productive and successful than centralised ones. Decentralised irrigation schemes enhance water productivity, nutritional outcomes, rural development, income generation, and ultimately food security, climate resilience and livelihoods (Burney et al., 2013; Osewe et al., 2020; IWMI, 2021), compared to centralised irrigation schemes (Mutiro and Lautze, 2015) as exemplified by experiences of the large Gezira Scheme (Sudan) and Office du Niger Scheme (Mali) in the past (Bjornlund et al., 2020).

Options for decentralised production and supply of food in marginalised communities include gardens (home-individual and community-collective) and mobile tuckshops (Gandidzanwa and Togo, 2022) (Figure 8). Home and community gardens can strengthen and intensify local food production, enhance food security (individual, household, and community), improve dietary intake and strengthen family relationships (Corrigan, 2011; Carney et al., 2012; Galhena et al., 2013; Egli et al., 2016; Modibedi et al., 2021). However, there is need to control and regulate agriculture in these settings to minimize pollution of available water sources, for example with heavy metals (Gandidzanwa and Togo, 2022).

Although the province is considered unsuitable for dryland cropping, households in the province mainly grow maize (62%), small grains (21.7%), nuts (10.7), beans (4.2%), and cowpeas (1.9%). However, the average household cereal production in the province was 123 kg in 2021 (ZimVAC and FNC, 2022c). In line with the studied areas' natural agroecology, food security can also be enhanced through rainfed production of drought resilient crops such as small grains including sorghum and millets (AU, 2023). A promising practice being promoted by the government is conservation agriculture under the auspices of the Climate-proofed Presidential Inputs Scheme (Pfumvudza/Intwasa) programme which seeks to climate-proof rainfed agriculture for food security (AU, 2023).

However, the interventions outlined above tend to be sector-based and have the potential to achieve sectoral security at the expense of other interlinked sectors and may worsen the irregular shape of the sustainability polygon for WEF nexus in rural areas of Matabeleland South Province (Figure 3a). Achieving centrality in the sustainability polygon requires solutions that harmonise and balance the security of WEF resources though integrated solutions.

The decentralised WEF technologies listed above can be integrated into synergistic packages leading to improved WEF nexus performance, for example hybrid solar-biogas-irrigation system (Winklmaier and Bazan Santos, 2018; Winklmaier et al., 2020; Corral Fernandez et al., 2022), solar powered irrigation schemes (Burney et al., 2010; IRENA and FAO, 2021), and waste-to-energy (septic tank-UASB system, BiogasDEWATS) (de Porres Lebofa and Huba, 2011; Lohani et al., 2015; Adhikari and Lohani, 2019) which have shown potential for success in Zimbabwe (Chinhoyi) and other developing countries including Ghana, Benin, India, and Lesotho. However, regulations and management are needed to minimize risk of groundwater over-extraction due to solar irrigation systems with groundwater (IRENA and FAO, 2021). Thus, decentralized water-energy- food systems harnessing the potential of groundwater, multi-purpose surface water storage, unconventional water and renewable energy can provide individuals and communities with affordable electricity, water, and food supply; increase nutritional intake and profitability of farming; and create employment opportunities for resilience and improved livelihoods (Ho, 2005; Winklmaier et al., 2020; Corral Fernandez et al., 2022).

With projections expecting urbanisation to continue rising from 53% (2020) to 70% by 2050 (Ritchie and Roser, 2018; UNEN and UN-DESA, 2020; OECD and FAO, 2022), the WEF nexus approach is a means to contain the rural-urban divide and offers avenues to advance rural development that would allow rural populations to reach the urban standard of living without having to migrate to urban areas or overexploit natural resources (UNDESA, 2021).

5. Conclusions

The Zimbabwe case study demonstrated using the WEF nexus approach through sustainability polygons in systematically assessing the rural-urban divide of WEF resources. The findings revealed that society has failed to include rural areas in sustainable development, especially in the global south. Evidence shows a wide gap between urban and rural areas, where the most vulnerable groups reside, in WEF nexus security, with the former leading by a significant margin. If the status quo persists, rural populations will continue to unsustainably exploit natural resources to the point of degradation and migrate in large numbers to urban areas. Thus, business as usual is not an option in addressing vulnerable groups' social and economic inequalities.

Transformative approaches such as the WEF nexus can potentially improve the lives of vulnerable rural populations. Pro-rural and pro-poor interventions simultaneously not only leave no "rural area" behind in the 2030 Agenda for Sustainable Development but fulfil their rights while protecting and conserving the ecosystems, thus preserving planetary boundaries.

Rural and urban populations are interlinked, for example, through the environment, ecosystems and resources. Therefore, it's either they progress together or lose together. Potential pro-rural nexus-friendly interventions include integrations of decentralised WEF solutions that promote simultaneous WEF security and circular economy, including renewable energy, sustainable groundwater use and localised food production. Such integrated WEF systems fully account for the interlinkages of water, energy, and food while optimising land use, recognising and addressing trade-offs and harnessing synergies among the sectors. Synchronised transformation of water, energy and food systems is inevitable to leverage synergies and minimise conflicts by co-locating the sub-systems to increase productivity.

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6. SUSTAINABILITY OF WATER USE SYSTEMS

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1. Introduction

Water is essential for life and economic activities. One of the Sustainable Development Goals set by the United Nations General Assembly is to ensure the availability and sustainable management of water and sanitation for all (Van Der Bruggen 2021).

With the growth in the global population and improved living standards, the demand for water has escalated. However, the availability of water resources has not changed. This asymmetry poses a significant challenge to improving water access and management. In response to this issue, this chapter considers how we may enhance the sustainability of water use systems.

Sustainability is increasingly viewed as a key goal of development and environmental management. Specifically, 'sustainability' refers to a system's ability to maintain productivity despite a major disturbance, such as that caused by intensive stress or a large perturbation (Conway 1985). This term is popular across numerous disciplines and diverse contexts, from discussions surrounding the concept of the maximum sustainable yield in forestry and fishery management to those that envision a sustainable society within the framework of a steady-state economy. Accordingly, the meaning of 'sustainability' strongly depends on the context in which it is applied and whether its use is based on a social, economic, or ecological perspective (Brown et al. 1987).

In recent decades, the availability of water resources has declined, marked by diminishing steady river flows and the depletion of groundwater, primarily as a result of the escalating demands of growing populations. Given that water scarcity—and, related, food security—cause environmental instability (Zarei et al. 2021), exploring the sustainability of water use systems is of practical significance.

2. Proportion of safely treated domestic and industrial wastewater flows

The main sources of wastewater include households (Zhang et al. 2015), services (Khan et al. 2020), and industries (Liu et al. 2023)—point sources of one or more pollutant(s) that can be geographically located. Diffused pollution from non-point sources, such as runoff from urban and agricultural land, can contribute significantly to wastewater flows; therefore, it is important to progressively include wastewater flows in global monitoring frameworks (Carstea et al. 2016, Nguyen et al. 2021).

Within this context, differentiating between different wastewater streams is important (Zhang et al. 2021). However, wastewater transported by combined sewers usually contains both hazardous and non-hazardous substances discharged from different sources, as well as runoff and urban stormwater, which cannot be tracked and monitored separately. Consequently, although the flow of generated wastewater can be disaggregated by source (e.g. domestic and industrial services), treated wastewater statistics are most commonly disaggregated by type (e.g. urban and industrial) and/or level of treatment (e.g. secondary) rather than by source.

Based on data from 140 countries and territories, approximately 58 per cent of household wastewater will be safely treated by 2022. However, wastewater statistics are lacking in many countries and reporting is low, especially regarding wastewater from industrial sources (Table 1).

Table 1: Proportion of safely treated domestic wastewater flows (percentage).

Regions	2020	2022
World	55.5	57.8
Sub-Saharan Africa	27.6	20.1
Northern Africa and Western Asia	62.7	63.8
Northern Africa	48.0	67.5
Western Asia	71.4	61.3
Central and Southern Asia	25.5	24.0
Central Asia	31.9	–
Southern Asia	25.2	23.6
Eastern and South-Eastern Asia	65.5	62.6
Eastern Asia	70.2	67.8
South-Eastern Asia	–	47.7
Latin America and the Caribbean	40.8	45.9
Oceania	77.7	79.2
Australia and New Zealand	78.8	92.2
Oceania (excluding Australia and New Zealand)	–	14.8
Europe and North America	80.4	86.5
Europe	76.5	74.3
North America	89.6	96.1
Landlocked developing countries	26.9	20.8
Least developed countries	22.3	17.5
Small island developing states	–	41.1

Source: The World Health Organization (WHO), 2022.

In many countries, wastewater statistics are in an early stage of development and not regularly produced or reported. Monitoring is relatively complex and costly, and data are not systematically aggregated at the national level and/or accessible—especially data on industrial wastewater, which are generally poorly monitored and rarely aggregated at the national level (Liguori et al. 2022). As a result, little is known about how much wastewater is generated and treated.

However, wastewater data are crucial for developing strategies for sustainable and safe wastewater use and reuse. Such strategies are notably necessary to support the health of the global population and broader environment as well as to respond to growing water demands, increasing water pollution loads, and the impacts of climate change on water resources.

3. Proportion of bodies of water with good ambient water quality

Ambient water quality refers to natural, untreated water in rivers, lakes, and groundwater and represents a combination of natural influences together with the impacts of all anthropogenic activities. Good ambient water quality is essential for protecting aquatic ecosystems and the services they provide, including the preservation of biodiversity (Vega Thurber et al. 2014); protecting human health during recreational water use; ensuring safe drinking water (Liew et al. 2023) and sources of human nutrition (through the provision of fish and water for irrigation); facilitating a variety of economic activities; and strengthening community resilience in response to water-related disasters. Notably, good ambient water quality is closely linked to sustainable water use systems.

The data is collected by UNEP and its Global Environment Monitoring System for Water (GEMS/Water) through electronic reporting in the global water quality information system GEMStat. At the national level, data reports are provided by the GEMS/Water National Focal Points or any other official counterpart appointed by the respective government. GEMS/Water offers consultation and support in selecting and compiling the required monitoring data, defining suitable river basin districts and delineating water bodies, as well as computing the indicator, upon request through its helpdesk. Data reported by the countries are checked for consistency with respect to the monitoring parameters, target values and spatial units and compared with monitoring data available in GEMStat, if applicable.Recognizing the differences in monitoring and data processing capacities among countries, the indicator methodology offers a progressive monitoring approach allowing countries to start with reporting based on their existing capacity and progressively enhance the data coverage and indicator significance with increasing capacity.

The indicator was computed by first classifying all the assessed water bodies based on the compliance of the monitoring data collected for selected parameters at the monitoring locations within the water body with parameter-specific target values:

$$C_{wq} = \frac{n_c}{n_m} \times 100$$

where C_{wq} is the percentage compliance (%), n_c is the number of monitoring values in compliance with the target values, and n_m is the total number of monitoring values.

A threshold value of 80% compliance was used to define water bodies as having "good" quality; that is, a water body was classified as being of good quality if at least 80% of all monitoring data from all monitoring stations within the water body complied with the respective targets.

In the second step, the classification results were used to compute the indicator as the proportion of the number of water bodies classified as having a good-quality status to the total number of classified water bodies, expressed as a percentage:

$$WBGQ = \frac{n_g}{n_t} \times 100$$

where $WBGQ$ is the percentage of water bodies classified as having a good quality status, n_g is the number of classified water bodies classified as having a good quality status, and n_t is the total number of monitored and classified water bodies.

As shown in Table 2, data from 2017 to 2020 indicate that 60 per cent of the assessed water bodies in 97 countries had good ambient water quality. Countries with robust monitoring systems showed positive trends; 44 per cent of the countries reporting in both 2017 and 2020 were on track to improve their water quality. However, the lack of data from particular regions poses a risk to the more than 3 billion people living in these areas where the quality of freshwater is unknown.

Table 2: Proportion of bodies of water with good ambient water quality (percentage). Source: World Environment Situation Room, United Nations Environment Program (UNEP

Regions	Bodies of water		Groundwater		Open water bodies		River water bodies	
	2017	2020	2017	2020	2017	2020	2017	2020
World	70.2	71.9	–	–	–	–	71.5	72.1
Sub-Saharan Africa	65.7	70.8	–	–	–	–	72.5	72.6
Central Asia	–	63.9	–	–	–	38.7	–	72.5
Latin America and the Caribbean	53.9	57.0	52.5	54.6	38.7	47.8	55.1	56.3
Oceania	–	87.2	–	84.2	–	90.3	–	–
Australia and New Zealand	–	87.1	–	84.1	–	90.3	–	–
Europe and North America	75.2	75.8	–	–	70.6	71.5	77.1	77.8
Europe	90.7	91.8	–	–	82.1	83.4	94.6	96.0
North America	–	57.7	–	–	–	–	–	57.2
Landlocked developing countries	–	73.3	–	–	–	–	–	77.4
Least developed countries	–	76.7	–	–	–	–	–	80.3

4. Change in water-use efficiency over time

Improving water-use efficiency is key to reducing water stress. As of 2020, an estimated 2.4 billion people lived in water-stressed countries, with almost 800 million living in high and critically high water-stressed countries.

Water-use efficiency was computed as the sum of the three sectors listed above and weighted according to the proportion of water used by each sector over the total use. The formula was as follows:

$$WUE = A_{we} \times P_A + M_{we} \times P_M + S_{we} \times P_s$$

where *WUE* represents water-use efficiency, A_{we} represents irrigated agriculture water-use efficiency [USD/m3], M_{we} represents MIMEC water-use efficiency [USD/m3], S_{we} represents services water-use efficiency [USD/m3], P_A represents the proportion of water used by the agricultural sector within the total used by all sectors, P_M represents the proportion of water used by the MIMEC sector within the total used by all sectors, and P_s represents the proportion of water used by the service sector within the total used by all sectors.

As shown in Table 3, water-use efficiency rose by 9% worldwide, from USD 17.4/m3 in 2015 to USD 18.9/m3 in 2020. This value ranges from below USD 3/m3 in economies that depend on agriculture to over USD 50/m3 in highly industrialised or service-based economies. The agricultural sector experienced the greatest increase in water-use efficiency (20 per cent) between 2015 and 2020; meanwhile, the industrial and service sectors demonstrated water-use efficiency increases of 13 and 0.3 per cent, respectively. Improving water-use efficiency requires more efficient irrigation, better agricultural management, tackling leakages in distribution networks, and optimising industrial and energy-cooling processes.

Table 3: Water-use efficiency (USD per cubic meter).

Regions	2015				2020			
	Agriculture	**Industries**	**Services**	**Total**	**Agriculture**	**Industries**	**Services**	**Total**
World	0.5	28.4	104.3	17.4	0.6	32.1	104.7	18.9
Sub-Saharan Africa	0.1	46.8	48.2	12.7	0.1	51.3	50.6	12.8
Northern Africa and Western Asia	0.4	132.0	59.0	11.7	0.5	71.0	52.8	11.2
Northern Africa	0.5	116.4	24.8	5.4	0.6	37.3	25.4	5.5
Western Asia	0.4	136.0	89.4	16.7	0.4	89.9	71.2	15.0
Central and Southern Asia	0.3	28.1	22.0	2.5	0.4	30.3	25.4	2.9
Central Asia	0.3	9.7	27.1	2.4	0.3	10.1	26.5	2.6
Southern Asia	0.4	36.4	21.6	2.5	0.4	41.0	25.3	2.9
Eastern and South-Eastern Asia	0.8	37.6	81.0	15.7	1.1	55.2	81.6	19.9
Eastern Asia	1.4	39.3	100.5	23.5	1.9	60.3	94.4	30.4
South-Eastern Asia	0.3	28.3	32.4	4.5	0.3	33.0	38.2	5.3
Latin America and the Caribbean	0.3	33.6	58.9	13.4	0.3	32.0	55.4	11.8
Oceania	1.1	70.3	215.6	58.7	1.4	85.6	358.4	76.8
Australia and New Zealand	1.1	70.7	221.8	58.3	1.4	86.4	381.0	76.7
Oceania (excluding Australia and New Zealand)	0.3	60.4	102.9	76.2	0.5	67.0	105.5	80.0
Europe and Northern America	0.3	19.8	213.0	47.5	0.3	20.1	220.9	49.5
Europe	0.6	29.4	178.5	58.8	0.6	30.4	179.0	60.7
Northern America	0.2	14.5	252.7	40.7	0.2	14.5	270.6	42.9
Landlocked developing countries	0.2	16.3	32.5	3.1	0.3	17.2	33.7	3.4
Least developed countries	0.3	70.3	31.4	3.9	0.3	90.9	36.5	4.7
Small island developing states	0.2	36.2	92.4	24.5	0.2	33.5	94.9	24.6

Source: Food and Agriculture Organisation of the United Nations (FAO)

5. Conclusions

This chapter draws three main conclusions. The first conclusion is that the establishment and management of water-use systems is crucial. First, water use systems must not only provide safe, clean, and reliable drinking water for humans but also meet standards for industry, irrigation, and ecosystems. Second, effective water environmental management can reduce the impact of human activities on water ecosystems and promote the sustainability of water-use systems.

The second conclusion is that efforts should be made to achieve sustainable water use and management. In particular, work should be done to ensure the equitable distribution, effective management, and economical use of water resources, including renewable water resources. To do so, it is necessary to implement water pollution control, limit discharge, strengthen the environmental monitoring of polluted water sources, save energy, and adopt low-carbon technologies.

The last conclusion is that the sustainable management of water supply systems requires the support and cooperation of the United Nations and other international organizations. Adhering to the "One Health" principle, realizing sustainable water supply management requires measures, policies, global cooperation, and scientific development for a sustainable future.

Despite advancements in water resource management studies, limitations in data availability and methodologies hinder comprehensive understanding. Future research should address these constraints by broadening data collection and employing diverse methodologies. Future directions include examining implementation effectiveness across regions, utilizing emerging technologies like AI and big data, and analyzing long-term climate change impacts. The significance of findings lies in providing actionable recommendations for policymakers, organizations, and stakeholders, contributing to sustainable water resource management and socio-economic development.

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7. IRRIGATION WITH NON-CONVENTIONAL WATER

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1. 1. Non-conventional water resources in hydrological planning

Pressure on the hydrological systems of many regions has progressively increased in recent decades as a consequence of: (1) significant population growth and the consequent increase in direct water demand; (2) the growing need for food, which has driven the expansion of irrigated agriculture as the main way to increase agricultural productivity; and (3) a greater concern for environmental conservation, leading to increased natural-environment water demand. Consequently, the progressive growth in total water demands, even to the point of exceeding the available natural water resources of those regions, is causing a structural water deficit in their hydrological planning (UNESCO, 2023). This water scarcity scenario is further exacerbated by the effects of climate change, which can lead to a progressive reduction in precipitation and thus in the available natural water resources.

The consolidation of this water deficit is often the source of conflicts among the different users of the affected management districts; conflicts that may reach inter-regional or international scale. Irrigated agriculture, as the sector that concentrates most of the water demand (around 70% globally, and over 80% in arid and semi-arid regions) can be seriously affected by these situations, since it is often considered a lower priority use than domestic or industrial use.

Mitigating water deficits by rebalancing water planning in water-scarce regions can be addressed either by acting on the demand or on the resources. Strategies to reduce agriculture water demand by decreasing the irrigation rate or the irrigated land could affect both food production as well as its security. Actions on resources cannot be oriented towards the extraction of greater flows from the deficit hydrological system, so the only feasible solutions involve relying on the contributions provided by external resources (water transfers) or the generation of new water resources outside the hydrological cycle. These new resources are called "non-conventional", and their application in irrigation is the topic of this chapter.

Non-conventional water resources offer complementary supplies that can be used to alleviate water scarcity in regions where conventional resources are already allocated. In agriculture, they can be the key to achieving the resilience of irrigated agriculture under the water-stressed situation faced by many regions. In general, non-conventional water resources are those that are not naturally or spontaneously available in nature, and require human intervention for their production and adaptation to specific uses. A comprehensive review of these resources (Karimidastenaei et al., 2022) includes artificial recharge of aquifers, agricultural drainage water, artificially generated rainfall through cloud seeding, desalinated brackish water or seawater, water harvesting through condensation, fog water harvesting, exploitation of fossil water reservoirs, urban wastewater reclamation and reuse, rainwater harvesting, and iceberg towing. Among them, the methods that can offer a massive water supply to agriculture are urban wastewater reclamation and reuse, and brackish water or seawater desalination; their applications to crop irrigation are presented below.

Wastewater reclamation and seawater desalination have become the main non-conventional resources for agricultural irrigation. Two factors can be highlighted that conceptually differentiate them: environmental and administrative factors. From the environmental perspective, seawater desalination involves significant greenhouse gas emissions due to its high energy requirements and massive discharges of brine into the sea, so its environmental effects are generally speaking of considerable concern. However, wastewater treatment and reuse is environmentally friendly since it fits perfectly within the basic principles of the circular economy by seeking to use the resource as many times as possible. Furthermore, it is necessary to highlight the transcendental role of irrigated agriculture in making the reuse of reclaimed water possible, to the extent that it is practically the only use for this resource, since it has little social acceptance for other purposes. From a legal or administrative point of view, wastewater reclamation is compulsory (at developed country level), whereas the implementation of seawater desalination responds to the need to alleviate water scarcity in a specific region and is thus a voluntary process.

CASE STUDY: Incorporation of non-conventional water in southeastern Spain.

A clear example of the incorporation of non-conventional water resources in water planning can be found in Spain, especially in the hydrographic districts of the southeast (Segura Basin and Andalusian Mediterranean Basins). In these districts, non-conventional water resources have gone from representing merely anecdotal uses to constituting a relevant part of the available resources. On the one hand, almost 100% of urban wastewater is regenerated in these areas and subsequently reused in agriculture. In addition, the importance of desalinated water for urban and agricultural supply has experienced constant growth, representing an essential component in current hydrological planning. Figure 1 shows the importance of non-conventional water resources in the Segura River and the Andalusian Mediterranean basins, where it is anticipated that, given the worsening of scarcity situations, desalination activities will be further developed in the future.

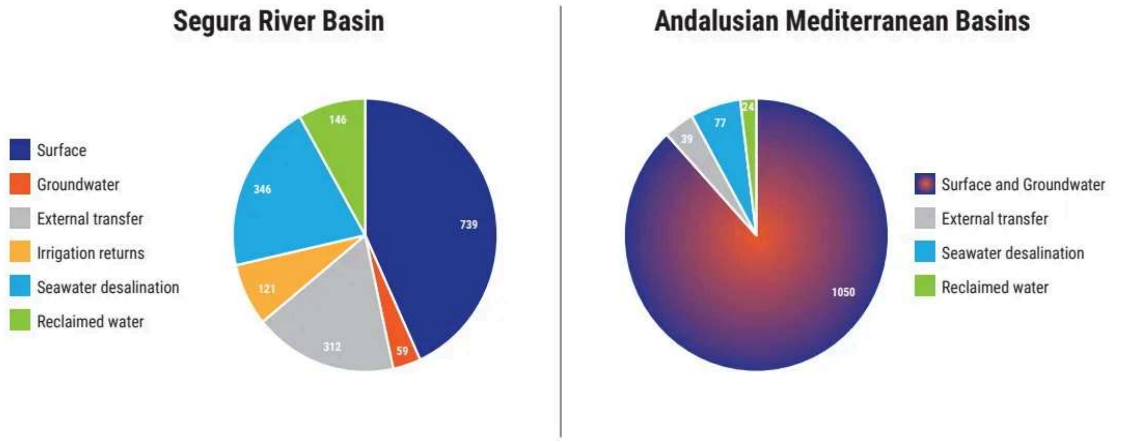


Figure 1: Available water resources (Mm^3/y) in the Segura River and Andalusian Mediterranean basin districts in Spain for the planning cycle 2022 – 2027.

Urban wastewater is defined as water that has been polluted because of human activities (domestic and industrial) or storm water runoff. Treated water refers to wastewater that has been subjected to a treatment process that allows its quality to be adapted to the applicable discharge regulations, whereas reclaimed water (RW) consists in treated wastewater that has been subjected to an additional or complementary treatment process enabling its quality to be adapted to the use for which it is intended, such as crop irrigation.

Desalination is generally understood as the process or set of processes aimed at eliminating or reducing the salinity of water to levels that render it suitable for the use considered. Desalination technologies in the field of irrigation can be applied to produce desalinated water (DW) from the following sources:

- Seawater, characterised by high and uniform salinity and virtually infinite availability.
- Brackish water, mainly groundwater, whose salinity is of geological origin or the result of marine intrusion and/or human activities. Its salinity and composition can be highly variable, and its availability is generally associated with the natural recharge of the hydrological system to which it belongs.
- Brackish treated water. Wastewater treatment plants located in coastal areas usually produce effluents with high salinity, as they are affected by seawater or brackish water seepage in the sewage networks, and must therefore be desalinated in order to be reused for irrigation purposes.

2. Status of non-conventional water resources for irrigation.

2.1. Reclaimed water.

The use of reclaimed water (RW) for irrigation, which dates back to 1912 through the irrigation of parks in California, is an established practice in several countries and regions of the world mainly affected by water scarcity. In Israel, for instance, RW has been reused for agricultural irrigation since the 1950s, and currently covers more than 50% of the agricultural water demand. The global use of RW has developed rapidly in the last two decades.

On a global scale, Jones et al. (2021) estimated an annual wastewater production of 359,400 Mm^3/y. They found that annual wastewater collection and treatment amounted to 225,600 and 188,100 Mm^3/y, respectively. Those figures indicate that about 63% and 52% of the wastewater produced worldwide is collected and treated, respectively, and that around 84% of the wastewater collected is treated. Wastewater reuse was estimated at 40,700 Mm^3/y, which represents about 11% of the total volume of wastewater produced, or 22% of the treated wastewater. Therefore, these data indicate that the remaining 78% (treated water not reused; 147,400 Mm^3/year) is discharged into the environment. This contrasts with the estimate of 171,300 Mm3/y of wastewater discharged directly into the environment with no treatment. Figure 2 shows global wastewater data in proportional terms (m3/y per capita for production; percentage of wastewater produced for collection, treatment, and reuse), allowing direct comparisons between countries.

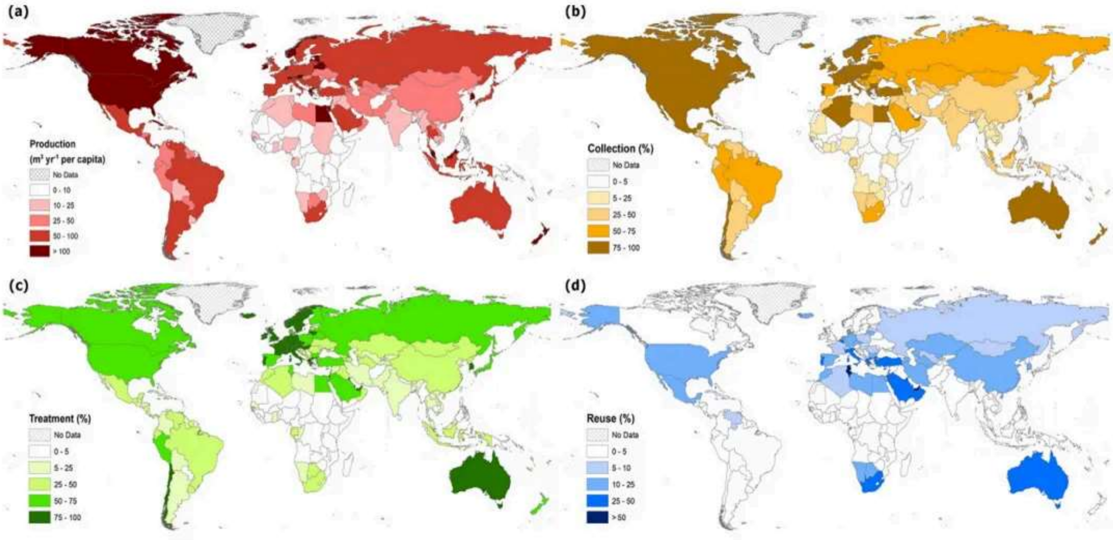


Figure 2: Wastewater production (m³/y per capita) (a), collection (%) (b), treatment (%) (c), and reuse (%) (d) at national level. Source: Jones et al., (2021).

The water reuse situation at European level is shown in Figure 3 (Hochstrat et al., 2006). These data indicate that the total volume of water reused amounts to 751 Mm3/y; this figure represents approximately 2.4% of treated urban wastewater effluent and less than 0.5% of annual freshwater withdrawals in the European Union. It should be noted that only Germany, Cyprus, Spain, France, Greece, Italy, Malta, Portugal, and the United Kingdom reuse significant volumes of water, albeit at quite different levels; 0.08% in the United Kingdom compared to 97% in Cyprus. Therefore, the European potential is far greater, in the order of 6000 Mm3/y, which is almost six times the current volume.

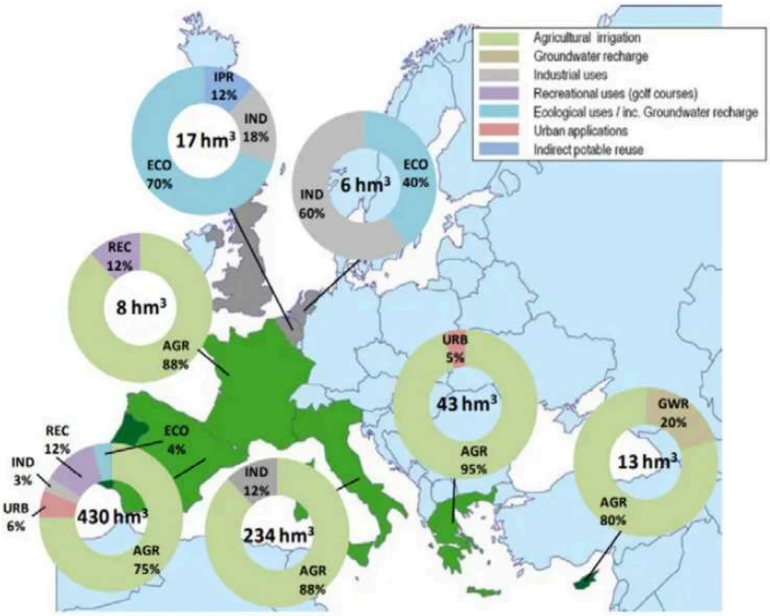


Figure 3: Status of water reuse in Europe. Source: Hochstrat et al. (2006).

CASE STUDY: The success of the regions of Murcia and Valencia (Spain) in water reuse for agriculture.

In the regions of Spain that suffer from a more pronounced structural water deficit, such as on the Mediterranean coast, the agricultural use of reclaimed water is of major importance, as it allows for more efficient management of water resources. In Spain, 4,726 Mm3 of wastewater is treated annually. Official global figures indicate that the volume of water reused in 2020 was 532 Mm^3/y, 72.4% of which was used for agriculture. Within this national panorama, the regions that reuse the largest volumes of water for crop irrigation are Valencia (199 Mm^3/y) and Murcia (105 Mm^3/y), which account for 72% of the water that is reused for agricultural purposes, or 57.1% of the total annual regenerated flow in Spain.

2.2. Desalinated water (DW).

At the outset, DW was used to supply domestic and industrial demands worldwide. However, as desalination technology has improved and the desalination cost has decreased, its application is being extended to other sectors, especially to agriculture. Thus, brackish-water desalination for crop irrigation has been reported worldwide and has increased dramatically in recent years. Moreover, large-scale supply with desalinated seawater (DSW) has emerged in the last 15 years as a promising water source for sustaining irrigated agriculture in some water-scarce Mediterranean regions growing high-return crops, such as south-eastern Spain and Israel, as well as on islands lacking freshwater resources, such as the Canary Islands (Martínez-Alvarez et al., 2016).

South-eastern Spain's agriculture has systematically suffered from a lack of water that has worsened over time. In the mid-1990s, more than 200 brackish-water desalination plants were installed on farms by farmers to resist a four-year drought period. The persistence of water scarcity problems, combined with the need to guarantee the existing high-return agriculture and to mitigate overexploitation of groundwater, led the Spanish government to sanction its AGUA Program in 2004. The Program was mainly aimed at building or upgrading 29 seawater desalination plants (SWDPs) along the Mediterranean coast to reinforce the water supply for agricultural, urban, and tourist use. That program sought to produce 693 Mm^3/y of desalinated water, 200 Mm^3/y of which would enhance the irrigation of about 105 ha. Figure 4 shows the current situation of DSW supply in south-eastern Spain, with nine SWDPs dedicating their production totally or partially to irrigation.

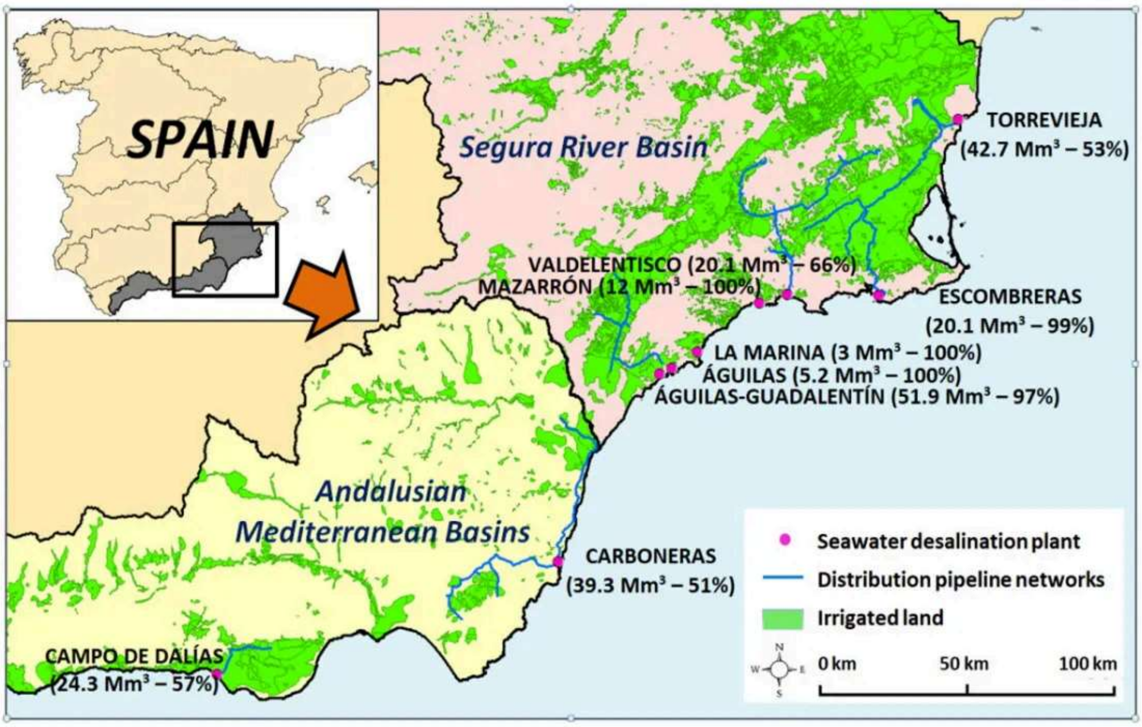


Figure 4: Status of DSW production for irrigation in south-eastern Spain. The figures show the total production and the percentage of agricultural supply at each SWDP. Source: Gallego-Elvira et al. (2021).

Israel has also dealt with severe water scarcity throughout its history, which has led its agriculture to continuously innovate to optimise water consumption and production. For these reasons, irrigation with underground brackish water and RW has been prevalent. Additionally, since 2006, DSW has become a realistic option for irrigation, with Israel being the only country that has sanctioned specific recommendations for domestic and agricultural use (Yermiyahu et al., 2007). The Israeli Desalination Master Plan was conceived in 1997 with the overarching goal of ensuring that water will be sustainable, available, and reliable in the required quantities, locations, and qualities. The plan intended to meet all Israeli domestic water needs with DSW by enhancing existing facilities and building new large-scale ones. The plan increased the total DSW production capacity to 750 Mm^3, with about 200 being intended for irrigated agriculture.

Seawater desalination technology is increasingly being considered as an alternative agricultural water supply in places such as Morocco, Tunisia, Egypt, Saudi Arabia, Mexico, South Korea, Chile, and California (Martínez-Alvarez et al., 2023a). This trend is expected to intensify in the near future, especially when considering the continuous improvement in membrane-based technology for seawater desalination.

CASE STUDY: Seawater desalination for irrigation in Israel.

Israel has five large-scale operational SWDPs using reverse osmosis technology; their locations and production capacities are detailed in Figure 5. The first plant (Ashkelon) was built in 2005. The other facilities (Palmachim, Hadera, Sorek, and Ashdod) were progressively inaugurated between 2010 and 2015. The Israeli Desalination Master Plan and the construction of the National Water Carrier, which is composed of a system of pipelines that receive the large amount of water coming from SWDPs and distribute it to all regions (Figure 5), have enabled Israel to put an end to its water crisis and dependence on the weather. The agricultural use of DSW is concentrated in southern Israel, where the low population density has enabled a substantial percentage of Ashkelon and Palmachim SWDPs supply to be used by farmers.

Figure 5: Location and production capacity of large-scale SWDPs in Israel.

3. Main regulations and characteristics of RW for irrigation.

The reuse of RW is a practice that must meet several technical requirements: satisfy the required water quality for its intended use; not deteriorate or affect the environments it reaches; not cause health problems to individuals in contact with the activity for which it is intended; and comply with the concept of sustainability.

Municipal wastewater reclamation for agricultural irrigation is common mainly in regions and countries such as the Middle East, North Africa, the Mediterranean region, Australia, China, Mexico, and the United States (UNESCO, 2017). Many organisations and countries have enacted laws, regulations, guidelines, and standards for irrigation with reclaimed water to guarantee the aforementioned requirements. Table 1 shows a summary of the main regulations issued worldwide.

Table 1: Summary of the main regulations published for irrigation with RW. Source: adapted from (Zhao et al.

Year	Country	Description
1996	Russia	SanPiN 2.1.7.573–96, Hygienic requirements to wastewater and sewage sludge use for land irrigation and fertilization.
2003	Italy	The Regulating Technical Standards for Wastewater Reuse.
2005	Portugal	The Guidelines for Good Practice of Water Reuse for irrigation: Portuguese standard.
2005	Japan	Guidelines for the Reuse of Treated Wastewater
2006	Australia	Australian Guidelines for Water Recycling: Managing Health and Environmental Risks.
2007	China	GB 20922-2007. The Reuse of Urban Recycling Water-Quality of Farmland Irrigation Water.
2007	Spain	RD 1620. Spanish Water Reuse Regulations.
2010	Israel	Effluent Quality Standards and Rules for Sewage Treatment.
2011	Greece	Determination of Measures, Conditions and Procedures for the Reuse of Treated Wastewater and Other Provisions.
2012	USA	Guidelines for Water Reuse.
2014	France	Regulations on the Reuse of Irrigation Water for Agriculture and Green Space.
2020	European Union	Regulation (EU) 2020/741 on minimum requirements for water reuse.

The specific energy consumption in a standard waste-water treatment plant ranges from 0.70 to 0.90 kWh/m3; this value depends on the plant size, quantity of organic matter removed and type of bioreactor aeration, especially in the tertiary treatment (Soto-García et al., 2013). Such a value is higher than that for surface water but lower than those for external transfers, groundwater, or desalination water (Martinez-Alvarez et al., 2016). The physicochemical characteristics of the RW can vary greatly, as they depend primarily on the urban-industrial origin of the wastewater being treated and, therefore, they are conditioned by each wastewater treatment plant. From an agronomic point of view, one of the most relevant characteristics in which most municipal effluents coincide is their significant concentration of essential inorganic plant nutrients and organic matter (Elgallal et al., 2016). After treatment, the concentrations of P, N, and especially K in the RW are higher than those of conventional waters and, therefore, from the point of view of efficient and sustainable agronomic practices, said nutrients should be considered in the fertigation programmes. On the other hand, the electrical conductivity (EC) of the RW is usually somewhat higher than the EC observed in conventional waters from the same region. This effect is particularly remarkable in treatment plants located close to the coast, which is justified by possible marine or brackish groundwater infiltrations in sewage collectors due to its progressive deterioration. Examples of high EC can be found in the RWs supplied by the treatment plants of San Pedro, San Javier, and Los Alcázares, located in south-eastern Spain, with average EC values of 6.2, 3.4 and 5.7 dS/m, respectively. These water supplies require desalination treatment prior to their reuse for agricultural irrigation. In addition, the concentrations of B, and especially Na and Cl, tend to be higher than in conventional waters and also increase as the treatment plants are located closer to the coast.

4. Main characteristics of DSW for irrigation.

From the water-energy nexus perspective, DSW is characterised by a very high energy consumption associated with its production and transport to irrigable areas; this is generally between 4 and 10 times higher than that of other water resources. As a consequence, production of DSW is also significantly more costly than conventional irrigation supplies, and its supply to farmers is also at much higher prices, which reduces its acceptance by farmers. These higher DSW prices can generate a significant impact on crop production costs, even compromising the economic viability of farms where DSW becomes a majority or exclusive supply (Martínez-Alvarez et al., 2017).

CASE STUDY: Energy consumption and cost of DSW.

The specific energy consumption in the SWDPs that supply agriculture in south-eastern Spain varies between 2.77 and 4.10 kWh/m3 for production, to which between 0.50 and 1.13 kWh/m3 needed for transport to irrigation areas must be added (Figure 6).

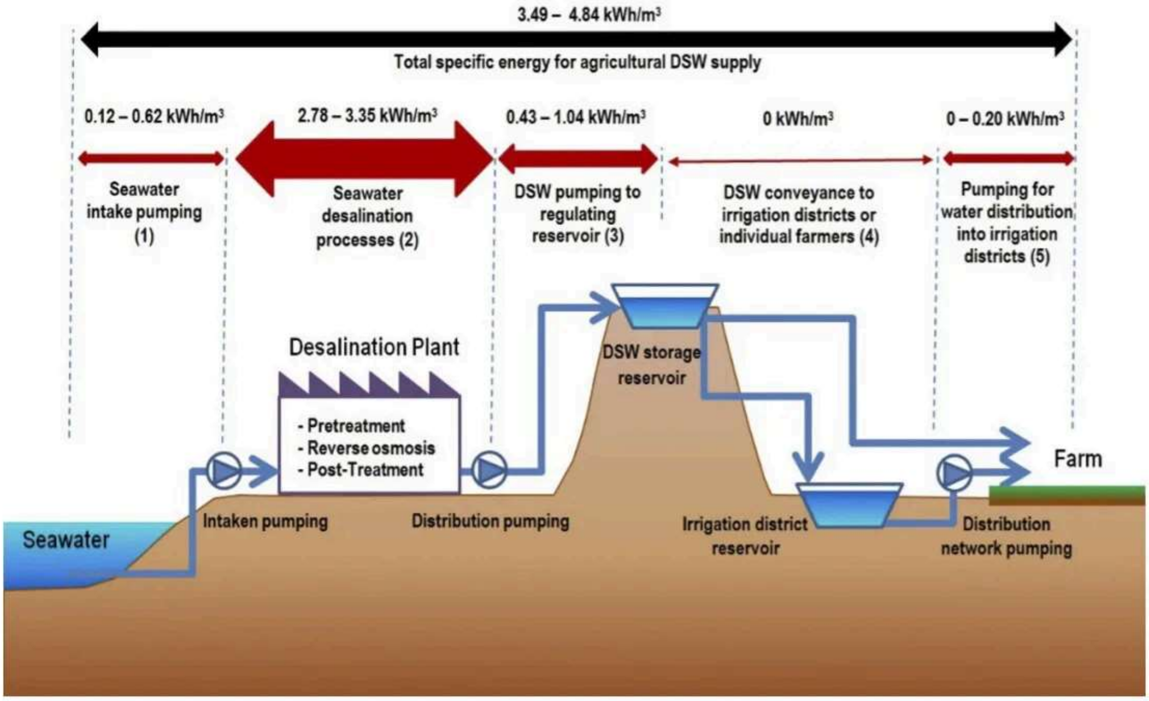


Figure 6: Specific energy consumption for the different stages of DSW production and supply for irrigation in south-eastern Spain. Source: Martínez-Alvarez et al. (2019).

The resulting total costs of DSW for irrigation, including production, transport and distribution in irrigation districts are between 0.50 and 0.65 €/m^3, which is also the usual price range for the final supply to farmers (Martínez-Alvarez et al., 2019). The high energy consumption associated with DSW production can also lead to significant greenhouse gas emissions, and therefore represents a strategy that is not aligned with climate change mitigation policies, unless DSW production can be linked to renewable energies.

DSW is generally characterised by physicochemical characteristics that differ considerably from those of conventional waters; this circumstance must be considered when it is to be used for irrigation. The water coming from a reverse osmosis process presents conditions that do not enable it to be discharged into the distribution systems due to its high corrosive capacity and potential to mobilise carbonate precipitates, making it necessary to subject it to a remineralisation process. In this process, depending on its intensity, the physicochemical characteristics of the osmosed water are adapted as follows:

- The pH is acidic (between 5 and 6), which after remineralisation becomes basic (between 8 and 9.5).

- The EC is generally between 0.4 and 0.7 dS/m and between 0.1 and 0.3 dS/m when a single or double step of reverse osmosis is applied, respectively, increasing slightly in the remineralisation process.

- Water hardness, associated with the concentration of Ca and Mg ions, is very low in osmosed water (2 or 3 mg/L), and increases during remineralisation by increasing the Ca ion concentration to values of 15-40 mg/L.

- Alkalinity, mainly related to the presence of bicarbonate and responsible for the buffering capacity of DSW, is also very low in osmosed water, rising to values ranging from 18 to 30 mg/L of bicarbonate in remineralisation.

Apart from these characteristics, which must be corrected regardless of the final use of DSW, two physicochemical aspects of DSW are of special relevance for agricultural supply. The first is the sodium adsorption ratio (SAR), which is utilised to determine possible effects on the structural stability of agricultural soils, and which, in osmosed water, presents values above 9, which is generally reduced in remineralisation to values below 5 to mitigate the risk of soil alkalinisation. The second is the B concentration, which can generate phytotoxicity problems in sensitive crops such as citrus and which usually presents high values (0.7 - 1 mg/L) in desalination processes with a single step of reverse osmosis. It is therefore common practice to apply a second osmosis step in desalination plants for agricultural supply in order to reduce that concentration.

All these circumstances make it highly advisable to regulate the quality of the agricultural supply of DSW to ensure that the physicochemical composition of the marketed product is guaranteed. This issue has only been addressed in Israel, where a series of recommendations for the agricultural supply of DSW for agricultural use are available (Yermiyahu et al., 2007).

5. Agronomic considerations for irrigation with non-conventional water resources.

The quality of irrigation water is an important issue when considering the substitution of some supplies for others, especially when dealing with resources of very different origins and physicochemical compositions, as is generally the case when replacing conventional with non-conventional water resources. Farmers must consider this circumstance, and adapt their irrigation management and fertigation programs to avoid possible effects on crop productivity and soil fertility. That adaptation normally entails upgrading the irrigation heads as well as increased operating costs, which could be compensated with other beneficial effects on crop yields or the total irrigation needs.

This section analyses the main agronomic questions to be considered when incorporating RW or DSW to crop irrigation, including: (1) the effect of water salinity on agricultural productivity; (2) the effect of water salinity on salt leaching requirements and, subsequently, on total irrigation needs; (3) the effect of the concentration of essential nutrients on fertiliser requirements and, consequently, on fertiliser costs; (4) the risk of phytotoxicity due to the relatively high content of B; and (5) the risk of soil alkalinisation due to the imbalance between monovalent and divalent cations.

5.1. Effect of water salinity on crop productivity.

Crop productivity is limited by the salinity of irrigation water (Maas and Hoffman, 1977). When crops are irrigated with water with an EC that exceeds its toxicity threshold, osmotic stress occurs, which can mainly result in reduced water uptake, a behaviour that impairs plant development and promotes potential yield loss. This issue has been extensively studied and addressed in the various versions of the FAO technical manual Water Quality for Agriculture (Ayers and Westcot, 1985) and subsequent works by other authors (Drechsel et al., 2023). The relative crop yield (Yr) as a function of the electrical conductivity of the soil saturation extract (ECs) is usually expressed as the crop yield obtained under salinity conditions divided by the crop yield obtained in the absence of salinity. That relative crop yield remains constant as ECs increases until a certain value is reached (ECs threshold), after which the relative yield decreases at an approximately linear rate with salinity, as shown in Figure 7.

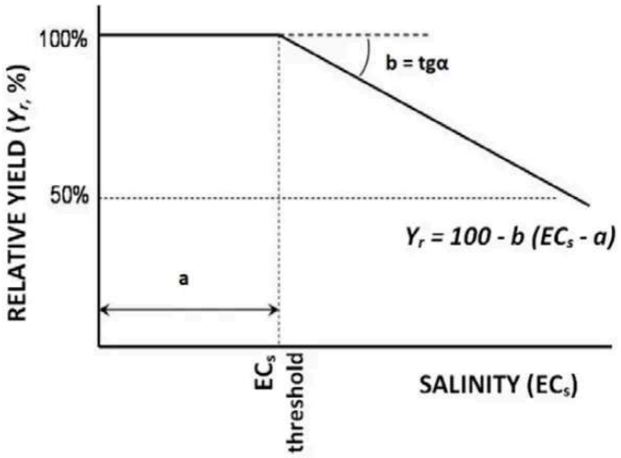


Figure 7: Relative crop yield function as a function of soil salinity.

ECs values are usually estimated as being 1.5 times the value of EC in irrigation water. Most arable and woody crops have these parameters tabulated, which enables their salinity tolerance to be assessed (Maas and Hoffman, 1977; Ayers and Westcot, 1985).

In this context, some RWs may have a high EC, affecting crop production. Negative impacts of RW on crop production due to increased salinity have been reported by several authors. For example, Pedrero et al. (2014), irrigated with RW with an EC = 3 dS/m for seven years in a Clementina mandarin orchard on Carrizo rootstock, and obtained a 40% yield reduction in the last year of the trial; Romero-Trigueros et al. (2014) detected yield losses of 20% in grapefruit variety Star Ruby on Macrophylla rootstock irrigated with RW with an EC = 3 dS/m; and Vicente-Sanchez et al. (2014), in an Iceberg lettuce crop irrigated with RW with an EC = 4.19 dS/m, observed a significant reduction in lettuce growth.

On the contrary, when replacing conventional water resources with DSW, the EC of the irrigation water tends to decrease, which can lead to crop yield increases. In this sense, Martínez-Alvarez et al. (2023a) reported a decrease in the EC of irrigation water as DSW was incorporated into irrigation in south-eastern Spain, and those authors analysed its impact on the yield of the irrigated crops covering the largest surface area in the region. Their results indicated that most crops had a Yr below their full potential productivity in the absence of salinity before DSW incorporation. Moreover, as the percentage of DSW increased the crop yield rose for all crops except the most salinity-tolerant ones (artichoke and broccoli). This rise was particularly relevant for apricot and peach trees as they have the highest sensitivity to salinity.

5.2. Effect of water salinity on total irrigation requirements

The total irrigation requirements of a crop (Nt) are greater than the net requirements (Nn), since more water is needed to counterbalance the losses caused by the growing conditions. An essential aspect in quantifying Nt is the salinity of the water, given that the accumulation of salts in the root zone of the soil must be removed through additional irrigation. Therefore, the effect of water salinity on Nt accounts for the fact that as water salinity varies, the salt leaching fraction also varies and, accordingly, Nt can change. The Nt for each crop and irrigation water salinity can be calculated according to the FAO technical manual Guidelines for Predicting Crop Water Requirements (Doorenbos and Pruitt, 1977). Leaving aside other local considerations regarding soil texture or irrigation system uniformity, Nt are calculated as Nn/(1-LF), where LF is the leaching fraction. The LF value is obtained as EC/(2·maxECe), where maxECe refers to the ECe producing a 100% decrease in crop yield, a parameter that is tabulated in the literature (Ayers and Westcot, 1985).

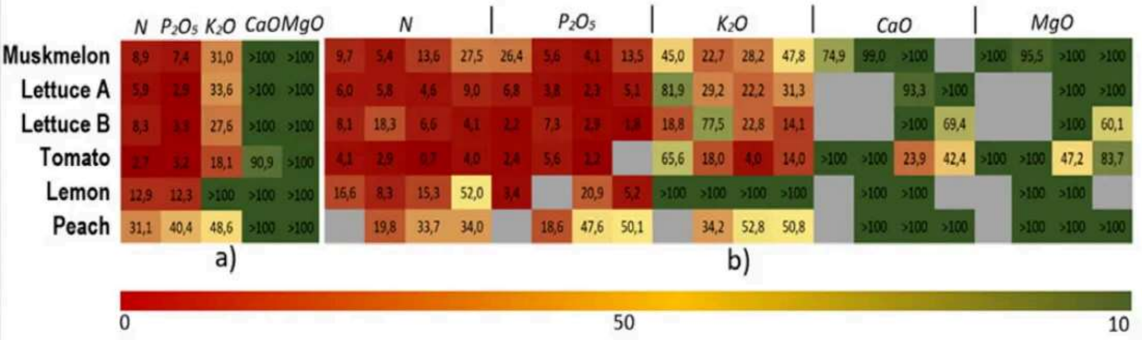
Therefore, a variation in Nt could be expected when RW or DSW replace other traditional agricultural water supplies. Since RW usually has a higher EC than that of conventional water in the same area, an increase in Nt could be expected when RW is incorporated. On the other hand, when DSW substitutes other traditional supplies, a decrease in Nt could be expected due to its lower EC. Martínez-Alvarez et al. (2023a) reported a progressive decrease in Nt as the proportion of DSW increased for several irrigated crops in south-eastern Spain. The decrease in Nt ranged from 2% in artichoke to 7% in apricot when incorporating 50% of DSW to irrigation, an increase that practically doubled when incorporating 100% of DSW.

5.3. Presence of essential nutrients and effect on fertigation.

The presence of N, P, and other nutrients in RW can significantly reduce fertiliser application, lowering not only the costs but also the environmental impact of fertiliser production. Bar-Tal et al. (2010) concluded in research conducted in Israel that the phyto-availability of nutrients in reclaimed water is generally equivalent to that of common mineral and organic fertilisers. Research in Israel has also shown that RW can provide at least 50% of the N and 100% of the P and K needed for low-demand crops such as citrus and avocado. However, the supply of nutrients from RW is a challenge because the nutrient inputs at each irrigation must be adjusted to the crop needs; with those needs changing depending on their phenological stage. Consequently, this situation can generate temporary imbalances between nutrient supply and plant needs unless it is managed agronomically in an appropriate manner.

CASE STUDY: Nutrition potential of reclaimed water for irrigation.

Maestre-Valero et al. (2019) calculated the percentage of nutrient requirements provided by different RWs for several irrigated crops in south-eastern Spain, which were estimated per crop cycle and per crop stage. Figure 8 shows that when the analysis was carried out for the complete cycle, some elements present in the RW, such as Mg, met 100% of the needs of lettuce and tomato. However, when considering the different stages of these crops, significant deficiencies of Mg and Ca were observed in stage 4 for lettuce (60.1%) and in stages 3 and 4 for tomato (47.2 and 83.7%, respectively). That study demonstrated that RW can indeed supply a large proportion of the nutrients needed by crops, especially in the case of woody crops. However, in order to detect possible nutrient deficiencies, each crop stage should be analysed independently due to temporal mismatches between the nutrient requirements of crops and the nutrients supplied by the water. Additionally, the importance of considering the nutrients present in RW was highlighted as they can allow significant cost savings in fertigation programmes.



	N	P_2O_5	K_2O	CaO	MgO
Muskmelon	8,9	7,4	31,0	>100	>100
Lettuce A	5,9	2,9	33,6	>100	>100
Lettuce B	8,3	3,9	27,6	>100	>100
Tomato	2,7	3,2	18,1	90,9	>100
Lemon	12,9	12,3	>100	>100	>100
Peach	31,1	40,4	48,6	>100	>100

	N				P_2O_5				K_2O				CaO				MgO			
Muskmelon	9,7	5,4	13,6	27,5	26,4	5,6	4,1	13,5	45,0	22,7	28,2	47,8	74,9	99,0	>100		>100	95,5	>100	>100
Lettuce A	6,0	5,8	4,6	9,0	6,8	3,8	2,3	5,1	81,9	29,2	22,2	31,3			93,3	>100			>100	>100
Lettuce B	8,1	18,3	6,6	4,1	2,2	7,3	2,9	1,8	18,8	77,5	22,8	14,1			>100	69,4			>100	60,1
Tomato	4,1	2,9	0,7	4,0	2,4	5,6	1,2		65,6	18,0	4,0	14,0	>100	>100	23,9	42,4	>100	>100	47,2	83,7
Lemon	16,6	8,3	15,3	52,0	3,4		20,9	5,2	>100	>100	>100	>100		>100	>100			>100	>100	
Peach		19,8	33,7	34,0		18,6	47,6	50,1		34,2	52,8	50,8		>100	>100	>100		>100	>100	>100

Figure 8: Percentage of nutrient requirements provided by RWs in relation to the nutrient requirements per cycle (a) and per crop stage (b). Grey squares represent crop stages that do not require that nutrient. Source: adapted from Maestre-Valero et al. (2019).

Unlike reclaimed water, DSW presents a lower concentration of essential nutrients for crop development than conventional waters. Specifically, it lacks Ca, Mg, and S, which are usually abundant in both surface and groundwater, so they are usually not considered in fertilisation programmes, or only play a secondary role in them. Therefore, fertigation programmes require adaptation to avoid nutritional deficiencies that affect crop production, with the consequent increase in fertiliser costs. Martínez-Alvarez et al. (2023a) analysed the importance of this economic impact by calculating the fertiliser requirements and the associated cost for the irrigated crops with the largest surface area in south-eastern Spain. As expected, there were increased fertiliser costs for all crops as the proportion of DSW increased. The increase was below 100 €/ha for all crops when considering 50% of DSW in irrigation water, but grew more than proportionally when considering 100% of DSW, reaching absolute values of about 400 €/ha for crops requiring higher doses of Ca and Mg (melon, broccoli, and artichoke). In general, it can be stated that this is a minor impact, as the annual operating cost of open field cultivation in south-eastern Spain is usually between 10,000 and 20,000 €/ha, so this only represents increases of between 1 and 4% of these operating costs.

5.4. Crop toxicity risk due to high boron concentration.

Boron is an essential trace element for the growth, development, and productivity of horticultural crops. Small B concentrations are necessary for plant growth, but signs of toxicity may appear when crops are exposed to higher concentrations. There is generally a small window between the concentrations leading to B deficiency and toxicity, so concentrations of around 0.2 mg/L in irrigation water may cover the needs as an essential micronutrient, but concentrations around 0.5 mg/L may lead to phytotoxicity problems in the most sensitive crops. The concentrations of B in surface irrigation water are generally lower than 0.1 mg/L, so supplementary inputs in the form of fertilisers (via micronutrient complexes) are often necessary for proper crop development. However, both RW and DSW can have high concentrations of phytotoxic elements such as Cl, Na, and B. Accumulation of these elements over time above certain thresholds can damage tissues and negatively affect metabolic processes, leading to yield reductions. It is important to note that permanent and perennial crops are more sensitive to ion-specific toxicities than seasonal or annual crops, where the exposure time is short and so high concentrations are not reached in the plant tissues. The most relevant risk is B phytotoxicity due to its high relative concentration, especially in DSW, which may be important for sensitive species/varieties in farms with a high percentage of DSW supply. The B concentration in DSW commonly varies between 1 mg/L and 0.5 mg/L, with such figures being common in plants with a single or double step of reverse osmosis, respectively. In the irrigated areas of south-eastern Spain, there is currently growing concern regarding this problem, given that the main risk factors converge in this region: a massive and growing incorporation into irrigation of water with a high B concentration (RW and DSW), a high presence of sensitive crops such as citrus, and semiarid climatic conditions. In contrast, recent research has shown the technical feasibility of on-farm boron-in-DSW reduction by reverse osmosis or ion exchange resins (Imbernón-Mulero et al. 2022a; 2022b).

The definition of B tolerance limits in irrigation water for different crops is a complex process involving a huge experimental effort. A number of factors based on crop variety, soil type, water chemistry, climatic conditions and irrigation management practices play an important role and can condition the results obtained. Regardless of this complexity, the goal of this field of work is to establish irrigation water quality limits, in terms of B concentration, which ensure long-term agronomic sustainability for crop irrigation (Grattan et al., 2015). The FAO technical manual Water quality for agriculture (Ayers and Westcot, 1994) provides crop tolerance thresholds linked to the B concentration in the soil solution. This information (Table 2) has become widespread as the main reference for this issue.

Table 2: Boron maximum permissible concentration in the soil solution without yield or vegetative growth reduction. Source: adapted from Ayers and Westcot (1985).

Tolerance	Boron (mg L-1)	Crops
Extremely sensitive	< 0.5	Blackberry, lemon
Very sensitive	Italy	The Regulating Technical Standards for Wastewater Reuse.
	Portugal	The Guidelines for Good Practice of Water Reuse for irrigation: Portuguese standard.
	0.5 - 0.75	Avocado, grapefruit, orange, apricot, peach, cherry, plum, persimmon, Kadota fig, grape, walnut, pecan, onion, apple
Sensitive	0.75 - 1.0	Garlic, sweet potato, wheat, sunflower, mung bean, sesame, lupine, strawberry, Jerusalem artichoke, kidney bean, snap bean, peanut
Moderately sensitive	1.0 - 2.0	Broccoli, red pepper, pea, carrot, radish, potato, cucumber, lettuce, pumpkin, spinach, tobacco, olive, roses
Moderately tolerant	2.0 - 4.0	Cabbage, turnip, Kentucky bluegrass, barley, cowpea, oats, corn, artichoke, mustard, sweet clover, squash, muskmelon, cauliflower
Tolerant	4.0 - 6.0	Alfalfa, purple vetch, parsley, red beet, sugar beet, tomato, cranberry, cotton, gladiolus, sesame, tulip, peppermint, rye.
Very tolerant	6.0 - 10.0	Sorghum, cotton, celery
Extremely tolerant	10.0 -10.5	Asparagus

It can be seen from Table 2 that woody crops, especially citrus (orange, mandarin, and lemon trees) and stone fruit trees (apricot, peach, and plum trees) are the most sensitive crops, whilst crops with short vegetative cycles, such as horticultural crops and herbaceous crops, are far less affected.

5.5. Soil alkalinisation risk

Another relevant agronomic aspect is the possible degradation of the soil structure by alkalinisation, which can result in the dispersion of clays and, consequently, affect its physical properties and crop yields. This risk, known as alkalinisation or sodicity risk, is associated with the relationship between the concentration of monovalent cations (Na+) and that of the divalent cations (Ca2+ and Mg2+) by means of the sodium adsorption ratio (Eq. 1), where all the concentrations are expressed in meq/L (Ayers and Westcot, 1985).

$$SAR = \frac{[Na^{+}]}{\sqrt{\frac{[Ca^{2+}]+[Mg^{2+}]}{2}}}$$

Both RW and DSW could favour soil alkalinisation. RWs can cause this because most of them present high concentrations of Na+, whereas in DSW it is due to the lack of Ca2+ and Mg2+ after the reverse osmosis and the remineralisation processes. The risk of soil alkalinisation in the medium and long term depends on the SAR and the EC under each water supply and is analysed with the graph shown in Figure 9.

CASE STUDY: Soil alkalinisation risk of irrigation with non-conventional water in south-eastern Spain.

Figure 9 shows the risk of soil alkalinisation in the medium to long term when irrigating with different RWs and DSWs in south-eastern Spain. All the RWs showed elevated SAR values, but the combination of SAR and EC in the graph did not show the alkalinisation risk, with the exception of La Unión wastewater treatment plant, which presented a slight to moderate alkalinisation risk. Dealing with DSWs, Torrevieja SWDP presented very low salinity and SAR, resulting in a severe risk of soil alkalinisation; Águilas SWDP had somewhat higher salinity and SAR values, resulting in a slight to moderate risk; whilst Valdelentisco SWDP had the highest salinity and SAR values, resulting in a lower risk than the other SWDPs.

In general, it can be stated that the risk of soil alkalinisation is moderate to high only when DSW is applied to irrigation and that the risk decreases when it is managed jointly with other surface water resources (Martínez-Alvarez et al., 2023b) and/or by implementing efficient fertigation programs by farmers by supplying Ca and Mg, which would slightly increase EC and clearly reduce SAR; resulting in lower alkalinisation risk (Figure 9).

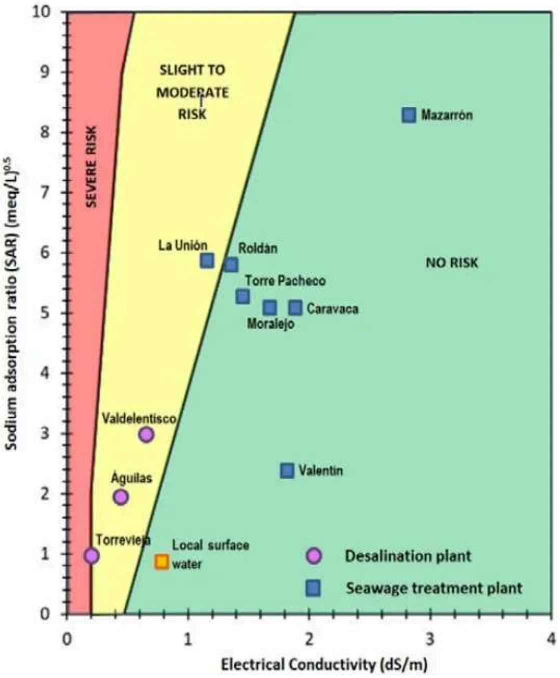


Figure 9: Mid- to long-term potential risk of soil alkalinisation for irrigation with RWs and DSWs produced in south-eastern Spain. Data from Maestre-Valero et al. (2019) and Martínez-Alvarez et al. (2023b).

Acknowledgements

This work is a result of the AGROALNEXT program and was supported by MCIN with funding from European Union NextGenerationEU (PRTR-C17.I1) and by Fundación Séneca with funding from Comunidad Autónoma Región de Murcia (CARM). The research was also funded by MCIN/AEI/10.13039/501100011033, project SEA4CROP (PID2020-118492RA-C22). The collaboration of Catedra Trasvase y Sostenibilidad–Jose Manuel Claver Valderas is acknowledged.

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8 . FINAL REMARKS

The preceding chapters have identified the principal challenges in the food production process within agriculture, particularly concerning water use. The critical role of engineering in devising and implementing solutions has been emphasized, contributing significantly to global sustainable development and peace.

Global challenges, exacerbated by the climate crisis and ongoing military conflicts, have intensified the problem of global hunger, as discussed in Chapter 2. To address the food security challenges posed by these crises, collaborative efforts from international organizations, local communities, stakeholders, and humanitarian agencies are imperative. Engineering services across various disciplines, including computer science, data engineering, infrastructure development, and natural and resilience engineering, are essential for supporting the recovery of agroecosystems in food production and nature conservation. Chapter 2 highlights the role of engineering within the World Food Program, with specific examples of large-scale infrastructure projects for humanitarian assistance, resilience interventions, and initiatives designed to enhance the resilience of food systems.

In regions facing water scarcity, it is crucial to implement sustainable and resilient water management strategies in response to the dual challenges of climate change and growing food demand. Integrated water resource management policies are vital to balancing the needs of agriculture, human consumption, and environmental conservation. Irrigation engineering plays a significant role in optimizing water use efficiency in food production, as well as supporting the livelihoods of rural communities dependent on agriculture as their primary source of income. New irrigation technologies have emerged and are being successfully applied in several countries, achieving a balance between agricultural economic viability, mitigation of desertification, enhanced food production, and natural resource conservation, as outlined in Chapter 3. The use of treated urban wastewater for irrigation presents a significant engineering and management challenge, offering an opportunity to supplement conventional water sources and reduce groundwater withdrawals, while also mitigating carbon emissions and protecting ecosystems, as discussed in Chapter 3a. Enhancing water productivity in irrigation requires technological innovations, improved technical training for irrigators and farmers, advanced management of irrigated areas, and the implementation of water-saving practices such as supplemental or deficit irrigation, as detailed in Chapter 3b.

The food processing industry is another major consumer of fresh water, with high demands for both quality and quantity. Mitigation measures are needed to address water shortages, as failure to do so may result in serious consequences such as rising food prices, food shortages, and environmental degradation. Water management technologies within the food processing sector (such as automated water flow systems, advanced washing systems, wastewater treatment, water recycling, and continuous monitoring of water use patterns) have the potential to generate substantial water savings. Water reuse systems are gaining increasing attention as promising technologies in the pursuit of sustainability. In many cases, water waste from food processing plants can be treated using advanced methods, enabling its reuse. Wastewater treatment processes vary according to the nature of waste and the type of industry, with methods such as membrane separation and filtration being employed to remove chemicals and microbes, or biological treatments used to eliminate emulsified grease, as discussed in Chapter 4.

Vulnerable groups, identified by factors such as their geographic location, lifestyle, and dependence on climate-sensitive natural resources for their livelihoods, include smallholder farmers, indigenous peoples, and rural populations, as highlighted in Chapter 5. These groups may struggle to meet their basic needs and face the risk of falling into deeper poverty. Inclusive and innovative approaches and tools can be employed to assist these groups, such as the water-energy-food nexus, which optimizes the interconnections between these vital natural resources for sustainable utilization. The potential for a just transition, as exemplified in Chapter 5, can be achieved through off-grid, in-situ, and decentralized solutions, including improved water access, treated wastewater reuse, energy supply, rehabilitation, and decentralized irrigation schemes, alongside infrastructure repair.

Sustainability is increasingly recognized as a central goal of development and environmental management, offering a critical framework for analyzing the water-energy-food nexus. Water use systems are essential for providing safe, clean, and reliable drinking water for human consumption, meeting the demands of industry and irrigation, and reducing the negative impacts on ecosystems, as discussed in Chapter 6. Key principles of good water management include equitable distribution, effective management, and economic sustainability. Achieving these objectives requires the implementation of water pollution controls, limiting discharges, strengthening environmental monitoring of polluted water sources, energy conservation, and the adoption of low-carbon technologies. The sustainable management of water supply systems demands innovative policies, global cooperation, and scientific advancements, with active participation from policymakers, organizations, and stakeholders, as emphasized in Chapter 6.

Non-conventional water resources, reclaimed water and desalinated water, are used in regions where there is a structural water shortage, due to population growth, the need to expand irrigated agriculture to increase food production and greater concern for environmental conservation. Chapter 7 addresses this issue and describes treatment and production technologies, with significant case study examples, which demonstrate the strategic and economic importance of these resources. The main regulations and characteristics of these water sources for irrigation are highlighted, as well as their importance for the sustainability of these systems. The agronomic considerations for irrigation with non-conventional water resources are explained, highlighting the effect of water salinity on crop production and total irrigation requirements, the presence of essential nutrients and effect on fertigation, as well as the crop toxicity risk due to high boron concentration, and the soil alkalinisation risk.

In conclusion, addressing the interconnected challenges of water use, food production, and sustainability requires a multifaceted approach that integrates engineering innovation, policy development, and global cooperation. The solutions outlined in this chapter underscore the critical role of technology and interdisciplinary collaboration in tackling issues such as water scarcity, food security, and environmental conservation. As we navigate the complex realities of a changing climate and growing global demand, it is essential that we prioritize resilient, inclusive, and sustainable practices in both agricultural and industrial sectors. Only through coordinated efforts across all levels of society—spanning local communities, international organizations, and scientific disciplines—can we hope to safeguard our natural resources, ensure food security for future generations, and contribute to a more equitable and peaceful world.

February, 2025

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World Federation of Engineering Organizations
Standing Technical Committee on Water (CW)