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# Towards sustainable desalination in the Mediterranean: integrating environmental, economics and social perspectives

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**Director of publication:** Dr. Sc. Robin Degron (Plan Bleu Director)

**Editors :** Dr. Sc. Robin Degron (Plan Bleu Director) and Mr. Samson Bellières (project manager and GIS expert at Plan Bleu)

**Authors:** Dr. Salah Eddine Sari Hassoun, Dr. Seyf Eddine Benbekhti, Dr. Hadjer Boulila, Dr. Mohammed N. Assaf, Mr. Firas Marsit (PhD), Dr. Samir Maliki, Dr. Nathalie Hilmi, Dr. Mourad Kertous, Dr. Abdelhadi Benghalem, Dr. Ouieme Sour, Dr. Najet Aroua, Dr. Imad Bouznad, Dr. Zebsa Rabah, Dr. Ziouch Omar Ramzi, Dr. Bengusmia Djamel, Ms. Maha el Mahdaoui (sustainability engineer), Dr. Widad Metajer, Dr. Ykhlef Soumia.

**Expertise carried out for the Plan Bleu for Environment and Development in the Mediterranean.**

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The articles compiled in this report adhere to a standard length to ensure consistency and accessibility. However, a limited number of submissions addressing highly innovative or methodologically complex topics that are minimally documented in the existing literature have been permitted to exceed this limit.

This editorial decision reflects the Plan Bleu commitment to advancing knowledge in emerging research areas where additional and comprehensive documentation is necessary to establish methodological foundations and ensure reproducibility. Articles exceeding the standard length have been subject to additional editorial scrutiny to verify that the extended content is essential for academic contribution and can't be reasonably condensed without compromising scientific rigor.

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This policy ensures that both established research areas (where concise presentation is feasible due to extensive existing literature) and emerging topics (requiring comprehensive methodological exposition) can contribute meaningfully to the scientific discourse while maintaining overall collection coherence.



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**Plan Bleu**
**UNEP/MAP Regional Activity Centre**
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# FOREWARD

The water scarcity and desalination sector development are pressing concerns for all Mediterranean countries of the Barcelona Convention. This unconventional water resource, while implemented to provide sufficient freshwater volumes to municipalities and other economic sectors often induces socio-economic issues, unintended and unpredictable negative impacts on the environment, exacerbating challenges that Mediterranean countries are already struggling with, such as climate change, biodiversity erosion, and resource depletion. This report provides an in-depth analysis and tailored recommendations adapted to the diverse contexts and legislative frameworks across the region with regional comparisons and national focus. It is important to note that this is the fourth report published by Plan Bleu to address the topic of desalination by encouraging academic reflection specifically for Mediterranean researchers, making it a pioneering effort to support regional environmental policies related to this topic.

Despite the emphasis on the negative aspects of the desalination sector, we have adopted a positive and optimistic outlook in the narrative and throughout the report. Each section lays on a dimension associated with the desalination sector and is relevant to the Mediterranean context including local features for southern and northern Mediterranean shores. The articles have been realized by the authors themselves and were then refined and compiled by Plan Bleu. They combine local experiences, rigorous skills in different areas of expertise and academic excellence, and offer diverse perspectives for greater sector resilience and sustainability, with the aim of providing the most appropriate support for the decision-making processes aligned with the sector. The findings bring a more nuanced vision of the desalination sector and valorize innovative, empirical approaches and ongoing efforts that can inspire desalination practitioners in the basin.

This report actively aligns with wider efforts at more global scales. It directly contributes to the United Nations Sustainable Development Goals (SDGs), notably to the SDG6-"Clean Water and Sanitation", providing analysis of desalination's role in ensuring water availability and sustainable water management. SDGs 12, 13 and 14 are also covered in this report, which encourages more sustainable methods for desalinated water production (use of sustainable energy, mitigation strategies), also highlighting the ecological impacts associated with brine discharges and how these can be reduced. On the other hand, this exploratory work contributes to the Mediterranean Action Plan & Barcelona Convention as it supports regional objectives to reduce land-based sources of marine pollution, including those from desalination. Moreover, it answers to the objective 3- "Ensure sustainable management of natural resources", and Objective 4: "Address climate change as a priority issue for the Mediterranean" of the Mediterranean Strategy for Sustainable Development (MSSD 2016-2025). Such collaborative work aligns with the Mediterranean Commission on Sustainable Development to bridge science, policy and practices.

It's important to bear in mind that this report is not developed in silo and is part of a long term vision of Plan Bleu on the Mediterranean water cycle and how this one evolves, reacts and must adapt to climate change pressures. Further activities on this topic will be pursued in the upcoming Program Of Work (2026-2027).

We would like to extend our sincere thanks to all the authors who have contributed to this ambitious effort. Their expertise, involvement, and collaboration have made this pioneering report possible and have set a strong foundation for future work in this controversial area. We also express our gratitude for the support received from UNEP/MAP and France, whose financial contributions have been invaluable in enabling this comprehensive study.

# Acknowledgements

The completion of this edited volume would not have been possible without the dedication and expertise of numerous individuals and institutions who contributed to both the research and dissemination efforts.

## Research Consortium

We extend our deepest gratitude to the ten research teams whose rigorous scientific contributions form the foundation of this volume:

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## Workshop and Dissemination

Special mention goes to all participants who attended the feedback workshop on Wednesday, September 3, 2025, contributing valuable questions and insights during the open discussion sessions. Their engagement enriched the final presentations and helped refine the conclusions presented in this volume.

We appreciate the technical support provided for the webinar organization and the seamless coordination that enabled researchers from across the Mediterranean to present their findings to a diverse audience of practitioners, policymakers, and academics.

## Regional Collaboration

This volume exemplifies the collaborative spirit essential for addressing Mediterranean water challenges. We acknowledge the researchers and institutions across the region who shared data, provided local insights, and facilitated the comparative analyses that strengthen the conclusions of this work.

# Glossary

### 1. Desalination sector

**Unconventional water resources:** Supplementary water resources that need specialized processes to be used as water supply when the natural tanks do not provide enough water in response to the water demand. Unlike conventional freshwater sources (rivers, lakes, groundwater), these alternatives require advanced treatment technologies or special collection methods to become suitable for human use.

**Desalination:** The process of removing salt and other excess minerals from seawater or brackish water to produce fresh water adapted for drinking, irrigation, or industrial uses. This is realized through various technologies including membrane-based methods (like reverse osmosis) and thermal processes (like distillation).

**Production systems (applied to desalination):** The organized industrial processes and infrastructure that convert seawater or brackish water into freshwater through coordinated and step-by-step operations. These systems commonly integrate intake facilities, pre-treatment units, desalination technology (membrane or thermal), post-treatment techniques, and distribution networks. They are designed to optimize water production capacity, energy efficiency, and operational costs while ensuring consistent water quality and managing brine disposal.

**Membrane technologies (applied to desalination):** A filtration process that uses semi-permeable membranes to separate freshwater from salt water. In Reverse Osmosis (RO) desalination (most commonly used), high pressure forces seawater through specialized membranes that allow water molecules to pass through while blocking salt and other contaminants, producing clean drinking water and concentrated brine waste. Other technologies exist such as Nanofiltration (NF), Ultrafiltration (UF), Microfiltration (MF) and Electrodialysis (ED).

**Thermal technologies (applied to desalination):** Heat-based desalination processes that produce freshwater by evaporating and condensing seawater. The main distributed thermal processes are multi-stage flash (MSF) distillation, multi-effect distillation (MED) and vapour compression variants – thermal and mechanical (TVC, MVC).

**Feeding waters:** The natural water sources that enter into a desalination production system. This includes seawater from oceans, brackish groundwater, or other saline water sources that require processing to remove salt and produce drinkable water. The quality and salinity of feeding waters directly affects the choice of desalination technology, energy requirements, and pre-treatment needs.
Brine: The ending byproduct of the desalination production systems. It's concentrated saltwater waste produced when freshwater is extracted from seawater. This byproduct contains 2-3 times more salt than original seawater and requires careful disposal to prevent environmental harm.

**Brine plumes:** Dense columns (denser than the ambient seawater) of highly concentrated saltwater that sink to the seabed and spread through the ocean when brine waste from desalination plants is discharged into marine environments. These plumes can create zones of elevated salinity that may harm local marine life and ecosystems if not diluted properly.

## 2. Research concepts and means mobilized:

**One Health approach:** An integrated, unifying approach to balance and optimize the health of people, animals and the environment. It promotes collaborative, multidisciplinary problem-solving to address health issues that are transversal and directly or indirectly impact humans, animals, and ecosystems.

**Econometric models:** Statistical models that use more or less complex mathematical equations to analyze economic dependencies and test economic theories. These models combine economic theory, mathematics, and statistical methods to quantify relationships between socio-economic variables, forecast future trends, and evaluate the effects of policy changes.

**Water Evaluation And Planning system (WEAP):** In this report, the WEAP model is used to simulate water demand at the regional and national levels, incorporating demographic projections, climate change scenarios, and socio-economic dynamics. This model assesses the needs for desalination and treated wastewater reuse, while identifying areas requiring priority of action investments.

**K-means clustering method:** In this report, the K-means clustering method is applied to categorize regions based on their vulnerability to water shortages, integrating climate, hydrological, and demographic data. This approach will facilitate the prioritization of actions and investments.

**Social Accounting Matrix (SAM):** SAM is an economic tool that provides a comprehensive snapshot of all transactions within an economy during a specific period, usually one year. It captures the flow of income and expenditures among different sectors, institutions, and factors of production

**Computable General Equilibrium (CGE):** is an economic modeling framework used to analyze how an economy reacts to changes, such as new policies or external shocks, at a single point in time. It simulates the economy by capturing the interactions between producers, consumers, government, and international trade, based on microeconomic principles and input data like a Social Accounting Matrix (SAM).

**Social Water Inclusion Index (SWII):** SWII is a comprehensive tool to measure and analyze the inclusivity of desalination benefits. The SWII evaluates key dimensions such as accessibility for underserved populations, afford

**Generalized Method of Moments (GMM):** This dynamic panel model is used to analyze desalination's socioeconomic impact in the Mediterranean may address three critical challenges: Dynamic Relationships, by incorporating lagged dependent variables to capture the persistence of socioeconomic outcomes like water affordability and equity over time; Endogeneity Concerns, by using lagged instruments to mitigate biases from feedback loops and unobserved factors like governance quality; and Cross-Country analysis, by leveraging panel data to account for both differences between countries and temporal evolution within them

# SUMMARY

# LIST OF FIGURES

**Chapter I. Global Issues and Sustainability of Desalination**



**Chapter II. Economy of Desalination and Sustainable Development Model**

**Chapter III. Regulatory Aspects and Public Policy Related to Water Management**



**Chapter IV. Integrated Approaches and Socio-Environmental Stakes**

# LIST OF TABLES

# INTRODUCTION

Dessalination Plant in Israel© Luciano Santandreu

## Mediterranean basin

The Mediterranean basin constitutes a rich and complex region. Indeed, the region is shaped by unique natural landscapes both from marine and terrestrial sides and endemic biodiversity. Surrounded by 21 countries the region also displays heterogeneous socio-economic and environmental contexts.

## Climate challenges

However, modern Mediterranean communities face a common challenge, resource scarcity. It is recognized that the basin is a climate change hotspot with more pronounced changes in its related environmental drivers. Since the pre-industrial period, the atmospheric surface temperature has increased by an average of +1,45 Celsius degrees. In fact, the key environmental drivers of the Mediterranean water cycle showcase major variations. Since the 1950s, evaporation rates in the Mediterranean region have shown an upward trend, driven largely by increasing temperatures and extended periods of sunshine (with higher solar radiation values and induced albedo). On the other hand, the water stress index is expected to increase globally at Mediterranean scale with more intense positive variations in already vulnerable areas.

## Water resources inequalities

In parallel to such growing pressures, the Mediterranean freshwater resources are increasingly depleted, with an initial spatial imbalance. Northern Mediterranean countries hold between two-thirds and three-quarters (approximately 67–74%) of the total renewable water resources in the region (IEMed, 2008; Plan Bleu, 2020). Projection models foresee a decrease in renewable water resources by 15–35% across the Mediterranean by the end of the century, primarily due to temperature increases of 3–5°C and a 10–20% reduction in precipitation (Plan Bleu, 2008; MedECC, 2020, Eekhout et al., 2025). In 2020, the renewable freshwater resources per capita displayed significant national disparities in their development trends. Slovenia, Croatia, and Albania recorded the highest values, with Croatia reaching up to 30,700 $m^3$/year/capita and Albania exceeding 10,000 $m^3$/year/capita, while Algeria, Tunisia, Libya, Egypt, Israel, and Syria recorded the lowest values, often below 1,000 $m^3$/year/capita, with Egypt as low as 589 $m^3$/year/capita.

Meanwhile, the Mediterranean population has increased by approximately 44% since 1990, adding over 160 million inhabitants to the region (Eurostat, Water statistics, 2024; Plan Bleu Observatory, 2024). Even if the water demand is increasing, the water withdrawal per capita records drastic decreases, highlighting the unbalanced trade-off between water demand and water uses. The majority of southern Mediterranean countries present lower water withdrawals than the third lowest water withdrawal of the northern mediterranean countries (France), in 2020. These disparities are further exacerbated by demographic pressures and evolving consumption patterns

Therefore, rising conflicts (between municipalities, industrial sectors, agriculture, etc.) may appear when it comes to water resources management, notably for areas that are exposed to drought and extreme heat events and which display low adaptation capacities. Actually, some mediterranean areas suffer from intense water scarcities inducing severe water shortages and limited access to the resource. In addition to the quantitative impacts on the resource, the natural water tanks are more and more polluted (either by anthropogenic pollution or microbiologic contaminations). Both quantitative and qualitative depletions are unequally distributed in time and are more and influenced by seasonality. Thus, municipalities may face greater water resource pressures during summer season than in winter season. However, this "classical" pattern shifts gradually with extended drought periods and more consecutive dry days through the year.

Historically, the Mediterranean has developed ingenious mitigation and adaptation strategies to cope with such water stresses, but most of them are no longer effective. Since the 1960s, several mediterranean countries progressively turned towards **unconventional water resources (desalination and wastewater reuse)** to address these persistent challenges. The desalination sector has been more adopted compared to wastewater reuse, notably in southern mediterranean countries (Plan Bleu, 2024; Angelakis et al, 2023). The first large-scale desalination units were implemented in the southern and eastern parts of the basin in Libya and Israel. From then, the technology has been gradually adopted by all the mediterranean countries, prioritizing energy-intensive production systems, thermal technologies (MSF, MED, VC, etc.). From the 90's, membrane technologies (Reverse-Osmosis) appeared and reduced the energy and economic costs. However, the desalination sector is still controversial with regards to its significant socio-economic and environmental impacts. The desalination sector offers many opportunities for supplying freshwater to municipalities and other dependent industries. Unfortunately, direct and cumulative impacts may appear on the surrounding socio-economic and environmental fabric. These impacts are numerous and well described in the literature and cover virtually the entire life cycle of the desalination plants from its installation to its dismantling. Also, the complexity of the topic induces plenty of environmental concerns, mostly for the coastal marine ecosystems exposed to desalination by-products, the brine discharges. There are many drivers that influence the brine volumes emitted in coastal areas and the associated impacts that are site and species-specific. Regarding the economic costs, they're massive both for the investment costs and the operationalization ones. Due to the complexity of production systems and the associated high technology, which are more or less energy-intensive, economic loads can sometimes be seen as a burden for investors and desalination operators. From a social perspective, the sector is still highly controversial and sometimes is not even known. Many studies point out a clear knowledge gap in the Mediterranean. Recognizing these challenges, Plan Bleu has positioned this work within established regional frameworks.

## Institutional framing

Plan Bleu aligns with the foundational objectives of the Mediterranean Strategy for Sustainable Development (MSSD), recognizing the urgency of advancing sustainable desalination in the Mediterranean. Indeed the water thematic being transversal, the Plan Bleu exploration studies on desalination is totally in adequation with the key components of the MSSD objectives (objective 2-"Promoting sustainable resource management, food production and food security") which echoes the sixth SDG, with its technical guidelines, with two MSSD indicators (MSSD indicators 12 and 13) and with the Barcelona Convention guidelines. According to the article 27.1, the contracting parties of the Convention undertake to cooperate in exchanging information on the use of best environmental practices. However, given the wide disparities observed in the various domains of the sector, this extract is put to the test. The "LBS Protocol, 2021" (Land Based Sources Protocol), of the Barcelona Convention doesn't include brines in the articles only mentioning industrial discharges into the coastal environments. Therefore, this edited volume can be seen as a solid foundation for a longer-term perspective, stressing the need for rigorous data-driven analysis including more in detail the issues and stakes associated with the desalination sector. This work can therefore be considered as a strategic, operational and information support tool for supporting decision-making processes for a more sustainable desalination future. Overall, whether a country is just beginning to explore the issue or has already made progress, this analysis can be a valuable resource, on the road to progressive and intelligent mitigation of the socio-economic and environmental impacts induced by desalination activities.

Within this framework, Plan Bleu launched a call for papers in 2024 allowing researchers to contribute to Plan Bleu exploratory efforts. Such academic inputs represent concrete and robust reflections of Mediterranean researchers specialized on desalination related topics. This call looked for papers that analyzed evidence-based contributions with tangible policy recommendations and concrete enablers. It centered on critical issues, exploring success stories and responsible practices in the Mediterranean, in the southern, eastern and northern sides, urging papers to uncover desalination diverse impacts across the region. 10 papers were selected according to their relevance and respective added value. A total of 15 researchers (from France, Algeria, Morocco, Italy and Tunisia). The selected studies explore important aspects of desalination, including economic viability, environmental impacts mitigation, inclusive decision-making, and governance frameworks. Their insights will help guide Mediterranean policymakers and stakeholders toward resilient and sustainable water management practices. The articles have been compiled in five distinct sections each of them shedding light on different dimensions associated with the desalination sector.

The first section **1.Global Issues and Sustainability** of desalination sets the stage by screening the Mediterranean desalination sector within global sustainability and climate change challenges. It details the strategic and crucial importance of the sector in the basin, highlighting the sector's resilience potential, its relationship with water scarcity and climate change, and other region specific risks. It also addresses the synergies with the sustainable development goals, notably with the 6th SDG while emphasizing risk mitigation and regional cooperation. Section **II. The economics of desalination and sustainable development models** presents a holistic economic analysis of desalination, offering an in-depth assessment of its viability within sustainable development frameworks. It explores the balance between affordability, accessibility, and environmental responsibility, drawing on economic assessments and feasibility studies, with a particular focus on Algeria. The authors examine how desalinated water can support not only urban water supply but also agricultural development, highlighting its potential contribution to broader socio-economic and sustainability goals. Section **III. Regulatory aspects and public policy related to water management** tackles the regulatory frameworks that influence or not the desalination sustainability. This part will assess to which extent the legal instruments and governance measures in the Mediterranean play in favor or against sustainable development of the sector, with a strong focus on Algeria evolving water policies. It advocates for transparent, adaptive, and integrated regulatory systems that enhance efficiency, accountability, and sustainability in the desalination sector. Finally, section **IV. Integrated approaches and socio-environmental stakes** proposes an original approach of social and environmental issues related to desalination by assessing and proposing more holistic approaches such as the "One Health approach and more inclusive, standardized and replicable indicator in order to reduce potential harms and optimize benefits from desalination units.

# CHAPTER I. GLOBAL ISSUES AND SUSTAINABILITY OF DESALINATION


Desalination plant on the Spanish coast © Wirestock

## Chapter I Introduction

This chapter provides a clear understanding on the desalination sector opportunities and related issues in the Mediterranean. It sets the frame of this controversial sector by addressing the needs of such desalination technologies, notably in vulnerable countries. The chapter also gives insights on the current state of the desalination framework, by examining how local desalination units need to intersect with broader international sustainability objectives, particularly in Mediterranean countries facing frequent water shortages, with complex socio-economic environments.

This chapter contrasts the nature of desalination development in the region. On one hand, the desalination contributes significantly to SDG6 by providing significant and safe access to drinkable water for Mediterranean populations. On the other hand, it presents complex environmental and social challenges, related to the desalination impacts (brine discharges and plumes, chemical pollution in coastal marine environments, energy consumption patterns, questions on distribution of desalinated water, social acceptability). The proposed analysis chapter highlights how these local challenges connect to global sustainability frameworks such as the Barcelona Convention and its Protocols.

Finally, based on the expertise of desalination practitioners, policymakers and researchers across different Mediterranean sub-regions, the chapter synthesizes and builds upon multiple perspectives on impact assessments, mitigation priorities and technological developments. These robust insights provide the basis for understanding how Mediterranean desalination activities can align with global sustainability standards while addressing region-specific vulnerabilities.
This first chapter can be considered as an overview that sets the analytical framework for the subsequent chapters, establishing the conceptual links between local desalination practices and global sustainability requirements.

# EXAMINING THE CONNECTIONS BETWEEN WATER RESOURCE SCARCITY, DESALINATION AND CLIMATE CHANGE: A STUDY SUPPORTING SDG 6 IMPLEMENTATION

AUTHORS: SALAH EDDINE SARI HASSOUN, SEYF EDDINE BENBEKHTI AND HADJER BOULILA

Dried riverbed and cracked soil © gettyimagespro

## Abstract

Achieving Sustainable Development Goal 6 (SDG-6) is directly impacted by two of the most pressing issues of the twenty-first century: the scarcity of water resources and climate change. Desalination is becoming more and more recognised as a crucial adaptation strategy for the Mediterranean (MED) region that is experiencing water resource scarcity as a result of population growth and climate change. This adaptive solution can support natural water reservoirs since it is not directly reliant on rainfall or climate fluctuations. This study is among the first to model multiple water-related variables for 19 MED countries during the period of 2000 to 2023. This paper investigates how SDG-6 and its sub-objectives are affected by the key identified factors: the amount of desalinated water produced per capita (DSL), the Falkenmark index (FLK), the amount of greenhouse gas emissions per capita (GHG), the gross domestic product per capita (GDP), and the world uncertainty index (WUI). The outcomes show that DSL has a low, positive, and significant impact on SDG-6, meaning that desalination represents a good adaptive solution to achieve SDG-6. However, FLK has a negative and significant influence, confirming that the MED is one of the most water-stressed areas in the world. GHG has also a negative and significant impact, supporting the idea that droughts, temperature and precipitation anomalies are getting worse due to global warming. The two control variables (GDP and WUI) both show negative effects, showing that some MED countries have high water management expenses and many uncertainties that significantly strain their national budgets and funding for water infrastructure.

**Keywords: Sustainable Development Goal 6; Mediterranean region; water resource scarcity desalination, climate change.**

## INTRODUCTION

Researching the connections between desalination, water resource scarcity, and SDG-6 requires an understanding of the fundamental components of water security, stress, and scarcity. According to UN-Water, water security is "the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability". However, both water stress and scarcity situations endanger water security. Water stress occurs when there is a period of time when the demand for water exceeds the supply. High water stress typically indicates that a nation is consuming an unbalanced amount of its freshwater resources, which may result in water scarcity, environmental harm, and resource depletion. Water scarcity is more severe than water stress because it is characterised by a lack of freshwater resources to meet regular water demands. Moreover, the UN divides the severity of water stress into different groups. Countries with less than 25% have no stress, those with 25–50% are low stress, those with 50–75% are medium stress, those with 75–100% are high stress or water resource scarcity, and those with more than 100% fall squarely into the critical stress or absolute water resource scarcity.

Furthermore, SDG-6 is to «ensure availability and sustainable management of water and sanitation for all». According to Sachs et al. (2025), SDG-6 comprises eight sub-objectives and addresses a distinct facet of resource management, sanitation, and water. SDG.6.1 represents universal and equitable access to safe and affordable drinking water. SDG.6.2 shows the access to adequate and equitable sanitation and hygiene. SDG.6.3 indicates the water quality and wastewater. SDG.6.4 represents water use and scarcity. SDG.6.5 shows the water resources management. SDG.6.6 indicates the water-related ecosystems. SDG 6.a represents the expanded water and sanitation support to developing countries (the international cooperation and capacity-building) and SDG 6.b shows the support for local engagement in water and sanitation management (the community participation). The SDG.6.4 and SDG.6.3 are the most closely related to tackling water stress and developing unconventional water resources (desalination). For the sake of environmental sustainability, economic growth, and public health, this SDG-6 must be met (UN World Water Development Report, 2021). 4.2 billion people lack proper sanitation, and 2.2 billion people still lack access to safely managed drinking water despite international efforts (UNICEF/World Health Organisation, 2023). Sachs et al. (2025) explore the SDG-6 index score, which is shown on a scale from zero to 100, and it can be understood as a percentage towards reaching the SDG-6s at their highest level. In 2024, Andorra and Monaco had the highest SDG-6 score in the world (100%), followed by Chile (96.76%) and Hungary (96.61%). In the MED region, Monaco had the highest SDG-6 (100%), followed by Greece (91.15%), Croatia (90.73%), and France (86.54%). This indicates that while some Northern MED countries have made great strides towards universal and sustainable access to clean water and sanitation, no single nation has yet to fully realise this goal worldwide. Nonetheless, Algeria (59.32%), Libya (55.71%), and Syrian Arab Republic (55.14%) have the lowest values. Additionally, we observed that SDG-6 decreased for nearly all MED nations when compared to three to four years ago, suggesting that water resource scarcity is starting to pose a threat to them.

The MED region's water resource scarcity is driven by a climate that ranges from semi-arid to arid, erratic seasonal variations in rainfall patterns, and dense populations with intense water use along the coast. Uneven distribution of water resources among nations, historical water stress, and management issues have triggered water resource scarcity in the MED (Le Page et al., 2020). MED water stress is typified by startling intra-regional disparities. Northern countries, such as Italy and the Po River basin in Spain, hold about 72% of the region's renewable water resources, but they usually have more resilient infrastructure to mitigate the effects of urban water shortages and droughts (Joint Research Centre, 2025). However, Southern and Eastern MED nations experience acute and chronic water scarcity, frequent severe droughts, and are unprepared to handle extra challenges (Kibaroglu, 2017). According to the World Bank (2025), the level of water stress in 2021 has reached an alarming level for severe MED countries (especially southwest MED), with Libya (817.14%), Egypt (141.17%) and Algeria (137.92%). Besides, the volume of renewable water per capita per year in the MENA region has decreased exponentially, reaching approximately 5,850 cubic metres (m3) per capita in 2020 (Statista, 2024).

Furthermore, the effect of climate change is influencing water availability through increased drought frequency, rising temperatures, and altered precipitation patterns. The MED region is becoming increasingly difficult due to factors like rising evaporation rates, and extreme weather events that affect infrastructure, groundwater recharge, and sea level rise endangering coastal aquifers (Intergovernmental Panel on Climate Change, 2023). The World Meteorological Organisation (2017) establishes a baseline by defining climate normal as 30-year averages of temperature, precipitation and other variables. The two most important factors affecting water availability and desalination effectiveness are temperature and precipitation. According to the Copernicus Interactive Climate Atlas (2025), the MED context's average annual temperature varied (increased) significantly from the average of 1970-1999 to 2023 with Bosnia and Herzegovina (+2.305 °C), Croatia (+2.255 °C), and Slovenia (2.22°C). Besides, the 2023 average annual precipitation level varied (declined) relatively to the 1970–1999 average with Morocco (-138.17 mm), Spain (-94.63 mm), and Malta (-74.86 mm).

Given that the MED region is experiencing water stress, water scarcity, and climate change, desalination may be a useful adaptation strategy to reduce the demand on freshwater resources and ensure a steady supply of water. In areas experiencing severe water stress, investing in desalination may be a necessary, albeit expensive solution to prevent economic losses from water resource scarcity, despite natural freshwater being more affordable. Desalination technologies are being actively developed and deployed as both a water scarcity solution and a climate adaptation strategy. With large desalination plants in Spain (Plan Bleu, 2024b), and other Gulf-adjacent countries, we are witnessing a growing adoption. In order to meet the pressing demands of industrial water expansion and drinking water supply, as well as to prevent actual threats to resource sustainability, many nations rely on desalinated water for more than 50% of their domestic water use (Bleninger and Jirka, 2010). Approximately 18,426 desalination plants were set up and running in 150 countries in 2015, supplying over 300 million people with 86.8 million m3 of fresh water daily (International Desalination Association, 2015). The Middle East and North Africa are hosting more than 50 percent of the world's desalination capacity in 2022 (Statista, 2024). Depending on capacity variations across MED countries, it is strategically significant for coastal urban areas. Their high operating costs, however, have an impact on accessibility, and their energy-intensive procedures increase carbon emissions (Mostefaoui et al., 2024). Therefore, rather than being viewed as a stand-alone solution, desalination should be viewed as a complementary measure to address the rise in water demand brought on by population growth, rising living standards, and climate change (Plan Bleu, 2024a). The desalination capacity in the MED region has increased to 15.6 million m3 daily, with Spain accounting for 35.53%, Algeria for 15.2%, Israel for 14.2%, and Egypt for 13.4%, according to Plan Bleu (2024b). There are now 2399 online desalination plants, with Spain accounting for 28.26%, Egypt for 25.51%, Greece for 15.13%, and Italy for 9.6%. According to Plan Bleu (2024b) notes, over 70% of installations in the MED are using reverse osmosis (RO), making it the most common desalination technology. For large-scale seawater desalination, this technology is the most energy-efficient choice, because its consumption is only 3–6 kWh/m$^3$. There are noticeable differences between the Northern, Southern and Eastern MED coasts in terms of desalination capacity and deployment technologies. The Northern MED region, driven by Spain, exhibits highly developed desalination technologies, facilities and tourism support. Followed by Greece, where its desalination focuses on small-scale and island-based facilities. Italy however has a more limited infrastructure. In the Southern MED region, countries place a high priority on desalination for municipal water security and to address extreme water stress conditions. Egypt and Algeria are among the leading producers, with Morocco and Tunisia following closely behind. In order to optimize efficiency in different local conditions, these nations utilize both RO and thermal desalination technologies in their mixed technology approaches. On the other hand, the most sophisticated desalination integration into national water strategies can be observed in the Eastern MED region, where Israel leads the pack, followed by Türkiye and Cyprus. Furthermore, there are several disparities in other aspects. For instance, modern RO plants or large-scale seawater plants are less expensive than smaller or older models from the 1970s. From an environmental perspective, managing brine discharge poses various obstacles in different parts of the MED region with desalination plants, which generate 1.5 to 4 litres of brine per litre of freshwater. For instance, Israel exhibits optimal efficiency ratios of 1.45 litres of brine per litre of freshwater, while nations such as Libya show ratios close to 4.1 litres of brine per litre of freshwater. Also, Spain and other Northern countries still mainly use conventional energy sources for their existing facilities, but more recent projects (in Egypt for example) focus on desalination that is powered by renewable energy and promotes sustainability. These regional variations imply that improved collaboration and technology transfer may aid in the optimal implementation of desalination throughout the MED basin, promising future and may be a useful substitute for reducing water stress and the strain on natural resources.

The objective of this paper is to investigate how DSL, FLK, GHG, GDP, and WUI affect SDG-6 for 19 MED countries during the period of 2000 to 2023. Despite cross-border water management challenges, institutional capacity disparities, rural versus urban access, and technical capabilities, these MED countries must invest in water infrastructure, given their varying levels of infrastructure development progress towards SDG-6. Therefore, the selection of these variables was obvious due to the significance of the topic and its title. By incorporating GDP and WUI as control variables, we can conduct a more holistic analysis. GDP is chosen because water demand is correlated with urbanisation, agriculture, and industrialisation, and high GDP (Northern MED) is correlated with water demand. Besides, water stress forces many high-GDP nations (like Israel) to invest in desalination in order to secure freshwater supplies, because they can invest in sophisticated, and renewable-powered desalination systems, but low-GDP nations might not have the necessary funds for desalination, which would exacerbate water insecurity, impede economic expansion, and it may lead to unsustainable water extraction (such as excessive groundwater use). The World Uncertainty Index (WUI) introduced by Ahir et al. (2022) however gauges global political and economic instability in a country. WUI is selected because it can show how higher levels of uncertainty can have a negative impact on water security and can worsen water access by lowering infrastructure investments and projects. Political tensions restrict technology sharing and cooperative approaches to addressing water scarcity, while maritime boundary disputes and resource conflicts impact regional cooperation on water management.

In the light of these statements, this analysis will attempt to address the following hypotheses:

### H1: Desalination improves the level of SDG-6

The first hypothesis investigates if desalination capacity directly improves water security outcomes. The theoretical basis is based on the fact that desalination is an unconventional source of water that can offer dependable freshwater access, especially in the Eastern and Southern MED region. Relaying to this hypothesis, countries with higher desalination capacity may also have better overall water and sanitation outcomes (better SDG-6).

### H2: Falkenmark index has a positive relationship with SDG-6

The second hypothesis analyses whether improved SDG-6 achievement is closely linked with increased water availability per capita. A positive connexion could support the concept that natural water abundance facilitates the achievement of water and sanitation objectives, as countries with higher water availability are not only less limited in their capacity to preserve water quality and deliver safely managed water services, but maintain water-related ecosystems as well.

### H3: GHG emissions have a negative impact on SDG-6

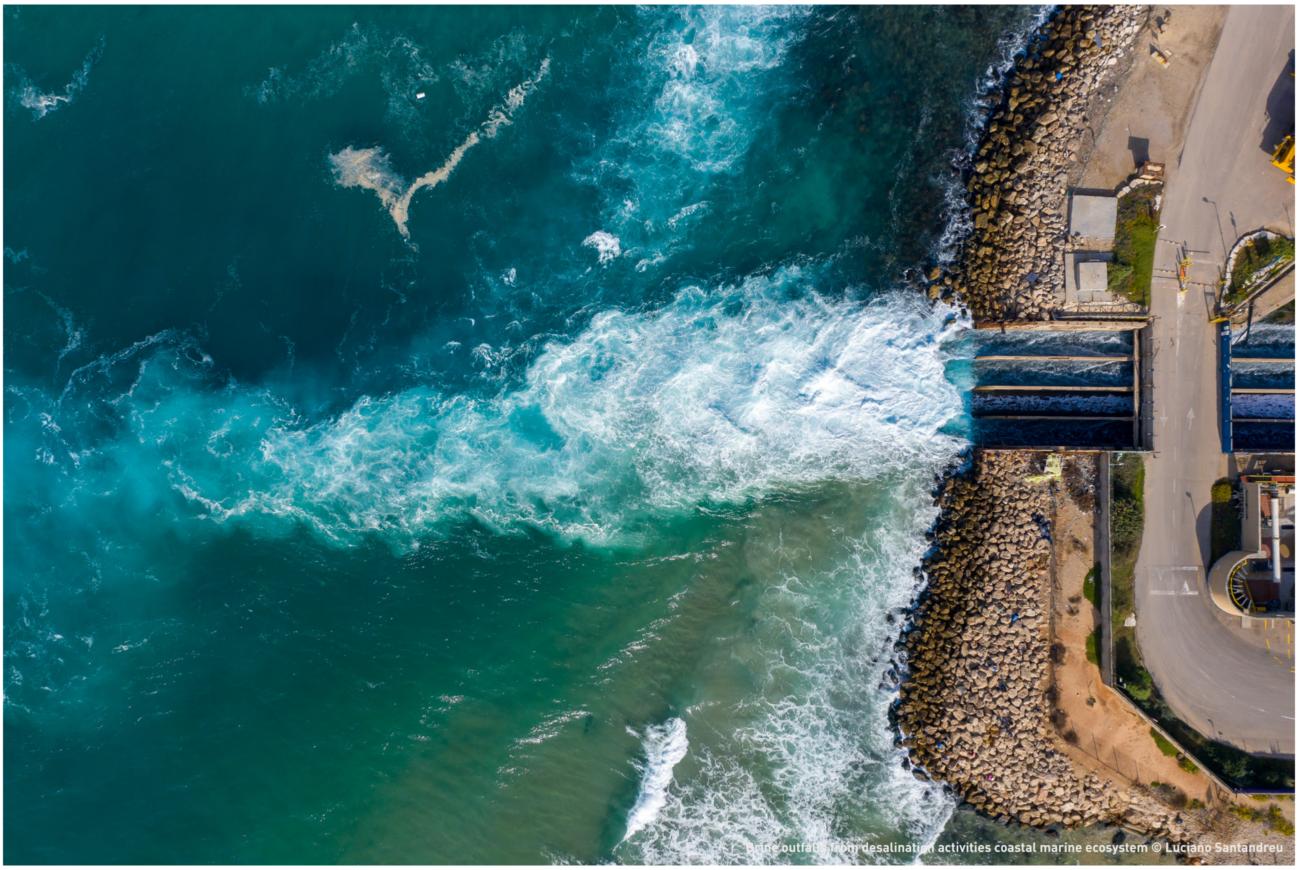
The third hypothesis examines the tension that exists between ecologically friendly water practices and high-carbon water systems. It is based on the idea that using a lot of energy to process, transport, and purify water results in a significant amount of GHG. High GHG emissions could be a sign of unsustainable practices endangering the environment and future water supplies. These emissions also contribute to climate change, temperature and precipitation anomalies, which exacerbates water resource scarcity, reduces the reliability of water systems, and creates a vicious cycle that impedes the achievement of SDG-6.

## METHODOLOGY

We will use Quantum Geographic Information System (QGIS), an open-source Geographic Information System (GIS) programme that allows users to create, edit, visualise, analyse, and publish geospatial data (QGIS Development Team, 2022). In the empirical result section, we employ QGIS to analyse the statistical aspects of a variety of variables, ranging from figure 1 to 6. Additionally, we employ GeoDa, which allows us to analyse the bivariate local indicators of spatial association (BLISA) and the results are in figure 7 and 8. GeoDa provides a number of exploratory spatial data analysis techniques, and has an easy-to-use interface with interactive visualisation tools, particularly for mapping, spatial regression analysis, and spatial autocorrelation statistics (GeoDa, 2023). In order to investigate local spatial patterns and spatial heterogeneity, Anselin (1995) defined BLISA as a statistical tool that maps spatial clustering or spatial relationships between two distinct variables across geographic space. It can reveal spatial interactions and non-stationarity by identifying locations where high values of one variable are surrounded by high or low values of another variable (Cluster Typology).

Following the spatial analysis, we examine the cross-sectional dependency (CSD) test with Breusch-Pagan (1980) or BP-LM statistic, which is appropriate when time (T) is large relative to cross section or number of country (N), and the test of Pesaran (2004) or PCD, which is generally regarded as the best overall CSD test. The Pesaran (2007) test or CIPS, which considers heterogeneity would be a suitable method to investigate the second-generation for panel unit root after it has been established that there is evidence of CSD. Moreover, the Jarque and Bera (1987) test examines whether the data are following a normal distribution or not by examining whether the dataset skewness and kurtosis are as expected under normal conditions. Then, both Pesaran and Yamagata (2008) and Blomquist and Westerlund (2013) tests are conducted after estimation to examine the slope homogeneity (SH). SH test shows whether the relationship between exogenous and the endogenous variable is consistent across various units in a panel dataset or not.

According to Baltagi and Pesaran (2007), one of the most delicate notions in panel data analysis is the heterogeneity issue. In this case, using the same model for multiple individuals or countries may result in biased outcomes. Methods like dynamic ordinary least squares (DOLS), fully modified ordinary least squares (FMOLS), and pooled mean group auto-regressive distributed lags (PMG-ARDL), among others, do not consider the heterogeneity issue. In order to deal with the heterogeneity issue, Koenker and Basset (1978) introduced quantile regression (QR) in panel data to provide estimations within the distribution's conditional quantiles, but this method was unable to handle other anomalies (linearity or fixed effect in panel data). Therefore, Machado and Silva (2019) suggest the method of moments-quantile regression (MMQR), which works well for handling unobserved heterogeneous effects across (N) or MED countries, permits examining effects at various quantiles, and is appropriate for policy impact analysis. This method is suitable for panel data models with individual effects and endogenous explanatory variables or dealing with non-normal distribution of the data. This approach has several advantages (applicability to non-linear models, computational simplicity, and models with multiple endogenous variables...etc).


Brine outfalls from desalination activities coastal marine ecosystem © Luciano Santandreu

# DATA AND MODEL

## *Data*

This study uses annual data over the period of 2000 to 2023 for 19 MED countries, including Croatia, France, Greece, Italy, Egypt, Lebanon, Syria, Albania, Slovenia, Bosnia and Herzegovina, Spain, Algeria, Cyprus, Türkiye, Malta, Libya, Morocco, Tunisia and Israel. Accordingly, the time period was selected due to the availability of data, especially SDG-6, which is only accessible from 2000. This paper employs the SDG-6 as the endogenous variable and only four of SDG-6's sub-objectives, because several data from the SDG-6 website are unavailable. The 1st sub-objective SDG.6.1 has two indicators "sdg_water", which relate to the rate of the population using at least a basic drinking water service and "sdg_safewat", which shows the rate of the population using safely managed water services. The 2nd sub-objective SDG.6.2 has also two indicators "sdg_sanita", which represents the rate of the population using at least a basic sanitation service and "sdg_safesan", which indicates the rate of the population using safely managed sanitation services. The 3rd sub-objective SDG.6.4 or "sdg_freshwat" shows the rate of available freshwater resources (freshwater withdrawal) or the level of water stress. The 4th sub-objective SDG.6.5 or "sdg_scarcew" indicates the scarce water consumption embodied in imports (m³ $H_2O$eq/capita). SDG-6 and sub-objectives indexes are on a scale from 0 to 100, except ("SDG-66_freshwat" and "SDG-66_scarcew"), but we use an index scale with values ranging from 0 to 1.

The first exogenous variable is the amount of desalinated water produced per capita (DSL), which represents a process of creation of fresh, and drinkable water by filtering out salt and other contaminants from diverse natural water reservoirs (aquiferous and brackish waters or sea). The unit is m³ per capita in a year and the related data were provided by Plan Bleu Observatory based on Global Water Intelligence Group and its DesalData database. The second exogenous variable is the Falkenmark index (FLK), which represents the country's internal renewable resources, such as groundwater from rainfall and internal river flows, which are referred to as renewable internal freshwater resources flows. Population estimates from the World Bank are used to calculate the amount of renewable internal freshwater resources per capita. The measure is m³ per capita in a year and the data are from World Development Indicators. The water resource stress and scarcity are estimated through FLK. The third variable is the annual greenhouse gas emissions (GHG) including land use and land-use changes over a 100-year timescale. GHG is a key component in understanding and managing human impact on climate change. It considers both carbon sinks and emission sources in terrestrial ecosystems. In addition to potentially removing $CO_2$ through forest growth and soil carbon storage, land use activities may also contribute significantly to emissions (such as deforestation). GHG emissions are calculated by multiplying activity data by emission factors, such as carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and fluorinated gases, using global warming potentials to convert emissions to $CO_2$ equivalent, and adding up all the gases and sources to get the total emissions. It is calculated by dividing GHG (tonnes of carbon dioxide equivalents) by the population. The unit is tonnes per capita in a year and the data are from Our World in Data. The fourth exogenous variable is the gross domestic product per capita (GDP), which is expressed as annually rate at market prices using constant local currency. The aggregates are expressed in US dollars and are based on constant USD prices from 2015. GDP is the total of the gross value added by all producers who are residents of the country, plus any product taxes and minus any subsidies that are not factored into the product value. The measure constant 2015 US$ and the data are from World Development Indicators. The fifth exogenous variable is the world uncertainty index (WUI), which represents the economic policy uncertainty (EPU). This variable can allow us to understand investment decisions in water projects, the pace of sustainability transitions impacts cross-border spillovers private and public investment decisions. The index is computed by counting the frequency of world uncertainty (or its variant) in the Economist Intelligence Unit (EIU) country reports. The index is normalised by the total number of words and recalculated by multiplying by 1,000. A higher number means higher uncertainty and vice versa. The data are from the World Uncertainty Index. The following table 1 provides an overview of the data details:

| Variables | Metrics/units | Source |
|---|---|---|
| Sustainable Development Goal 6 (SDG-6) | Scale of 0 to 1 | https://dashboards.SDG-6index.org/explorer |
| SDG.6.1 related to water service (SDGW) | Scale of 0 to 1 | https://dashboards.SDG-6index.org/explorer |
| SDG.6.2 related to sanitation service (SDGS) | Scale of 0 to 1 | https://dashboards.SDG-6index.org/explorer |
| SDG.6.4 related to freshwater (SDG-FR) | % of available freshwater resources | https://dashboards.SDG-6index.org/explorer |
| SDG.6.5 related to water scarcity (SDGSC) | $m^3$ $H_2Oeq$ /capita | https://dashboards.SDG-6index.org/explorer |
| The amount of desalinated water produced per capita (DSL) | $m^3$/capita | https://www.globalwaterintel.com/ |
| The Falkenmark index (FLK) | $m^3$/capita | https://databank.worldbank.org/source/world-development-indicators |
| The amount of greenhouse gas emissions per capita (GHG) | Tonnes $CO_2$ equivalent /capita | https://ourworldindata.org/ |
| Gross domestic product per capita (GDP) | constant 2015 US$/capita | https://databank.worldbank.org/source/world-development-indicators |
| World Uncertainty Index (WUI) | Index | https://worlduncertaintyindex.com/data/ |

**TABLE 1**
**Data details**

### *Models*

The Eq. (1) shows the subsequent model, which assesses the influence of DSL, FLK, GHG, GDP, and WUI on SDG-6 or SDG variable:

$$SDG= f\ (DSL, FLK, GHG, GDP, WUI) \qquad \textbf{(1)}$$

To minimise certain econometric issues, we transformed the data into natural logarithm. This linearized the non-linear relationships, stabilised variance, decreased heteroscedasticity, and made the coefficients interpretable as elasticity. Therefore, all variables were log-transformed for the econometrics analysis and the basic model is displayed in Eq. (2):

$$LnSDG_{it} = \varphi_i + \beta_1(LnDSL_{it}) + \beta_2(LnFLK_{it}) + \beta_3(LnCARBON_{it}) + \beta_4(LnGDP_{it}) + \beta_5(LnWUI_{it}) + \varepsilon_{it} \qquad (2)$$

Where LnSDGit represents the natural logarithm of the SDG-6 in the country (i) at the time (t) and it can be substituted by its sub-objectives (LnSDGW, LnSDGS, LnSDGFR, or LnSDGSC). i is the intercept or the constant term and it can indicate the fixed effects produced by "i". 1 to 5 represent the elasticities of the exogenous variables. it is the error of specification and is used to describe all variables that are not included in this study in the "i" at "t".

The equation of the MMQR is described in Eq. (3)

$$Q_\tau(LnSDG_{it}) = \varphi_\tau + \beta_{1,\tau} LnDesal_{it} + \beta_{2,\tau} LnFalk_{it} + \beta_{3,\tau} LnGHG_{it} + \beta_{4,\tau} LnGDP_{it} + \beta_{5,\tau} WUI_{it} + \varepsilon_{it,\tau} \qquad (3)$$

Where Q represents the quantile effect or the th quantile of LnSDG.

## EMPIRICAL RESULTS

### *Spatial analysis*

Figure 1 describes the spatial distribution of SDG-6 in 2023. It is clear that Northern MED countries have a better level of SDG-6 than Eastern and Southern MED countries. The primary explanation for this observation is that there is a disparity in economic growth, which means higher GDP/capita translates into more investment in SDG-6. Additionally, SDG-6 is strained by high levels of water stress and vice versa. Northern MED countries have more desalination plants and recycling facilities, and are associated with better water policies.

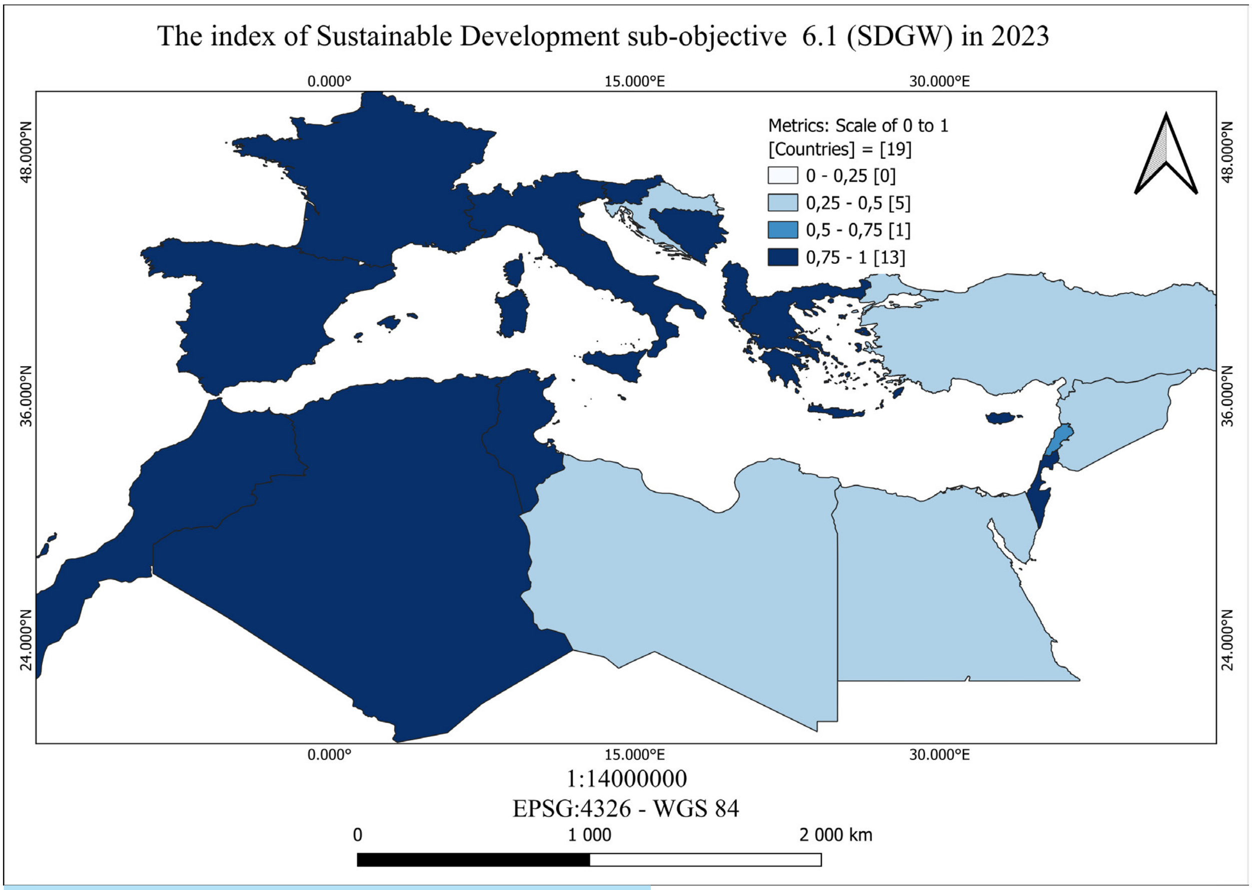



**Figure.1** *The index of Sustainable Development Goal 6 (SDG-6) and its sub-objectives in 2023*

Figures 1.a and 1.b show that the majority of MED nations have accomplished SDG.6.1 and SDG.6.2. Figures 1.c and 1.d, however, illustrate the reasons for the differences between the MED countries in the North, South, and East. The majority of Southern and Eastern MED countries experience high water stress, as shown in Figure 1.c, with the exception of Morocco and Lebanon, which experience moderate water stress. While Türkiye and Cyprus experience low water stress. Figure 1.d illustrates that except Israel and Lebanon, the majority of the Southern and Eastern MED countries, as well as Croatia, Bosnia and Herzegovina, and Albania, experience moderate water resource scarcity.

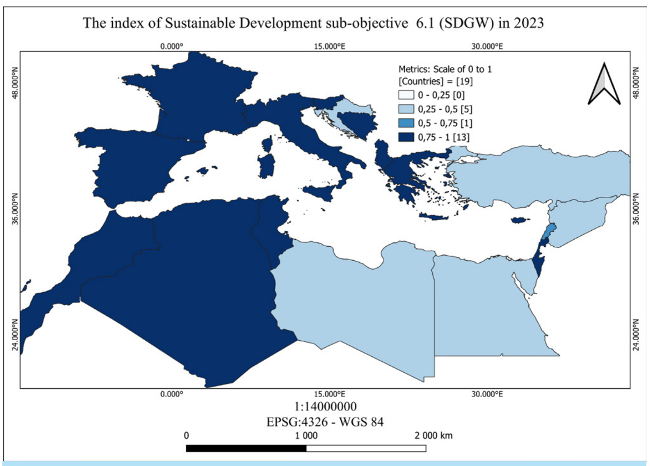



**Figure.1.a** *SDG.6.1 related to water service (SDGW)*

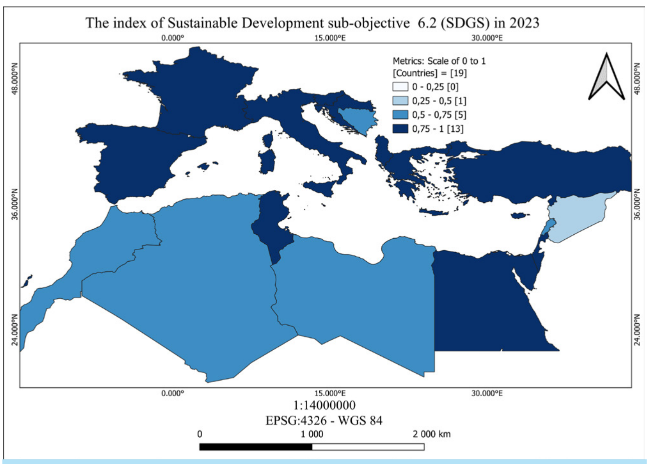



**Figure.1.b** *SDG.6.2 related to sanitation service (SDGS)*

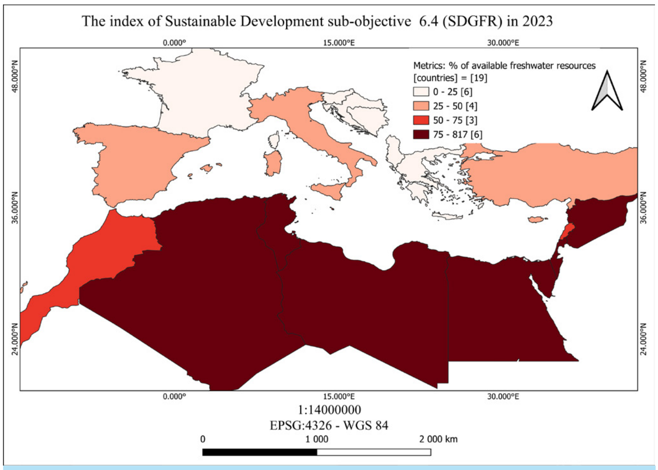



**Figure.1.c** *SDG.6.1 related to water service (SDGW)*

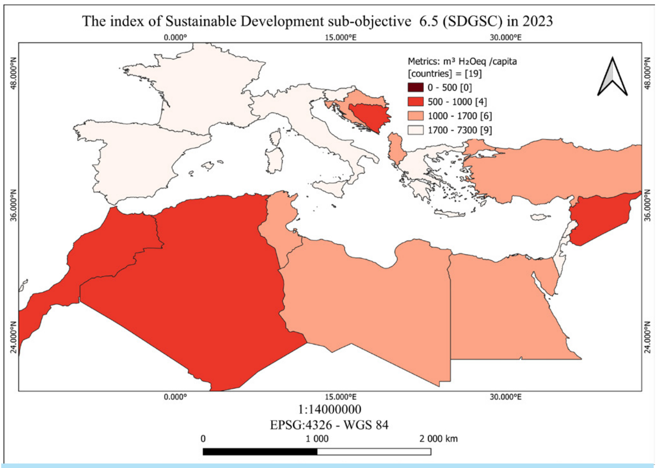



**Figure.1.d** *SDG.6.5 related to water scarcity (SDGSC)*

Figure 2 shows that the amount of desalinated water produced per capita in 15 countries ranges from 0 to 30 m3 per capita, whereas Spain has 31 m3 per capita, Israel and Cyprus form the third group with 60-90 m3 per capita, and Malta has 104 m3 per capita. The above data demonstrate that the high costs of desalination, which necessitate large capital (plant construction) and operating (energy) expenditures, continue to plague many nations.

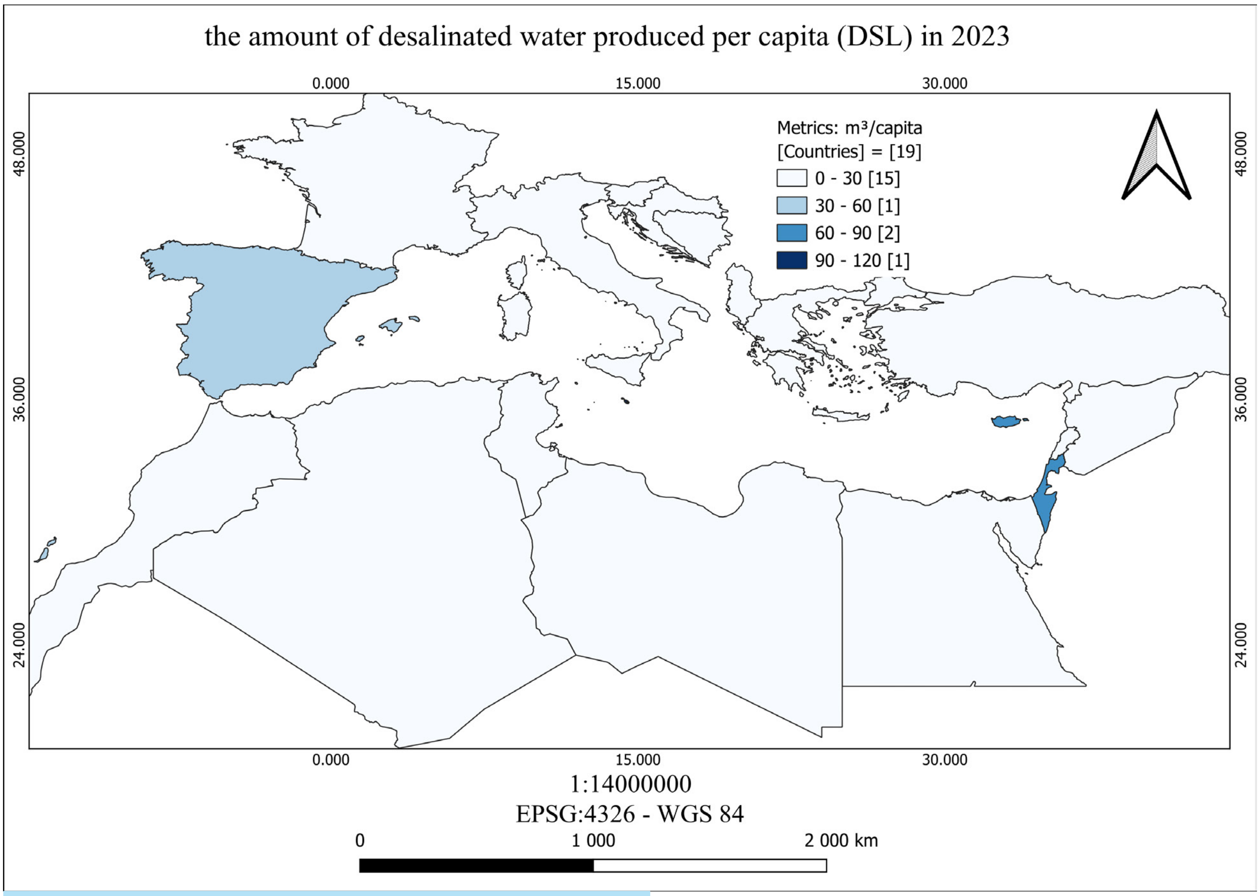



**Figure.2** *The amount of desalinated water produced per capita (DSL) in 2023*

The Falkenmark index (FLK) in 2023 supports the SDG-6 findings as displayed in figure 3. All Northern MED countries as well as Türkiye, with the exception of Malta that have more than 1700 m3 per capita. Water scarcity is a major problem in the other MED countries, with the exception of Morocco, Lebanon, and Cyprus. These results demonstrate the drought and desertification that the Southern and Eastern MED countries experience, as well as the rising temperatures and droughts brought on by climate change.

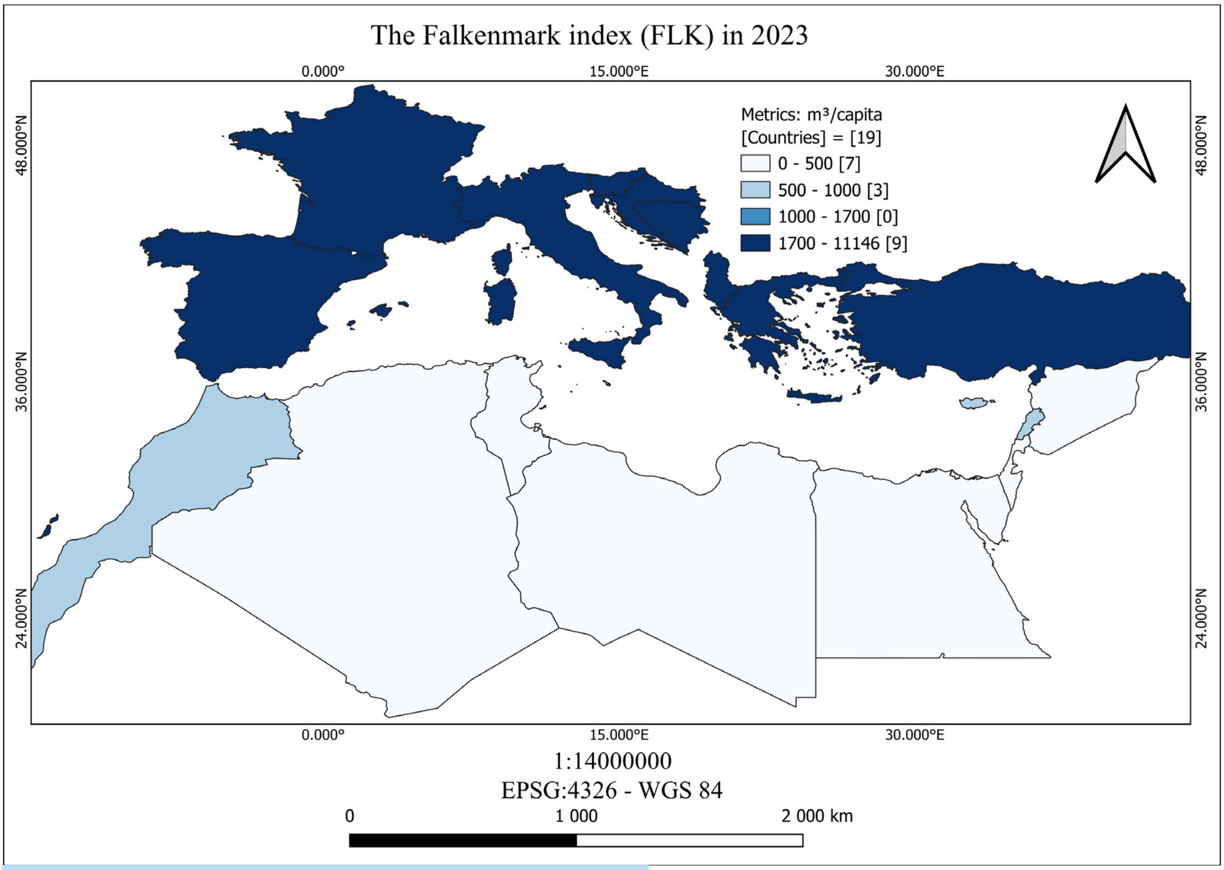



**Figure.3** *The Falkenmark index (FLK) in 2023*

In contrast to water stress or desalination capacity, which exhibit pronounced north-south disparities, figure 4 displays the amount of greenhouse gas emissions per capita (GHG), which is fairly evenly distributed across MED countries because they continue to rely on fossil fuels. North-South disparities and policy priorities are being balanced by industrialisation trends. As they are trying to convert energy and desalination systems to renewable sources in order to meet SDG 13 (Climate) and SDG-6.

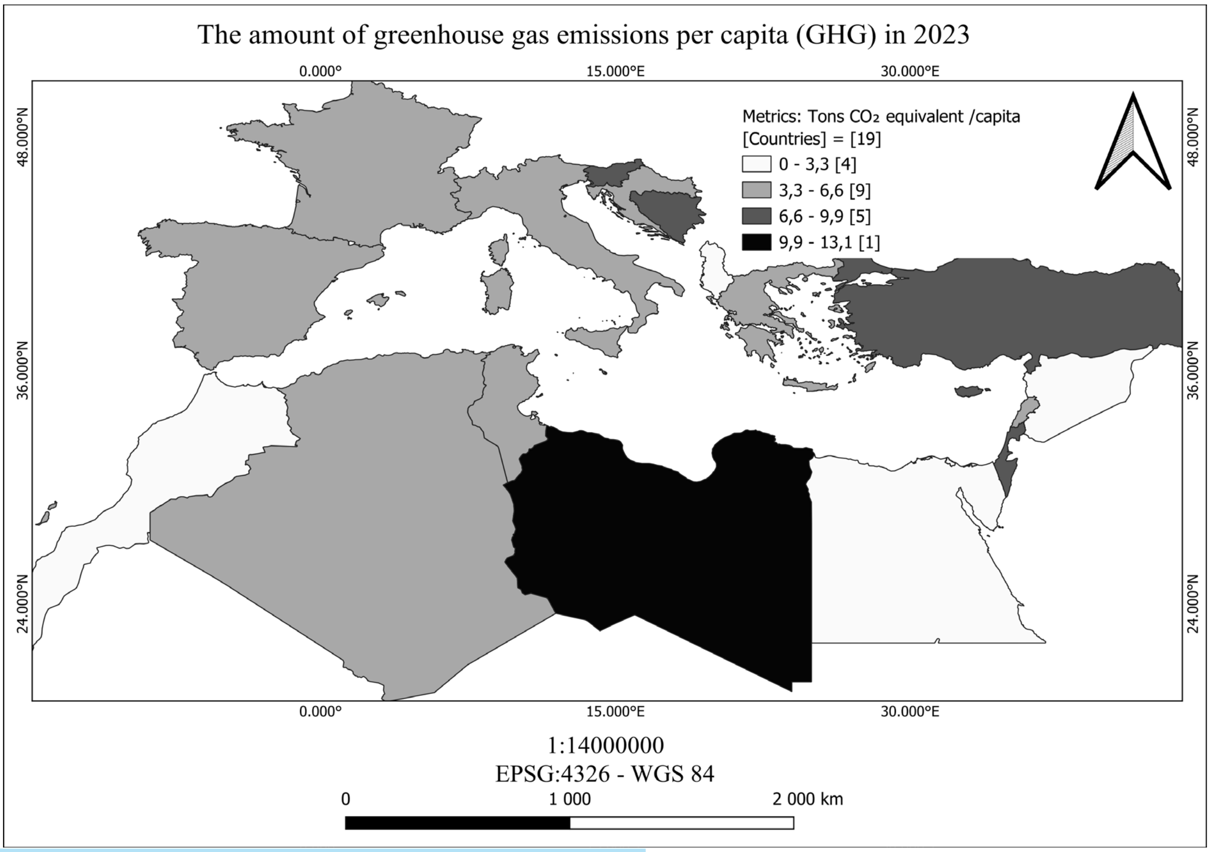



**Figure.4** *The amount of greenhouse gas emissions per capita (GHG) in 2023*

Figure 5 illustrates the disparity in GDP between MED countries. Northern MED nations have substantially higher GDP per capita than Southern/Eastern MED nations. Compared to the Southern and Eastern MED, the Northern MED is wealthier due to technology, tourism, manufacturing, luxury goods, agriculture, and renewable energy. The GDP of the Southern and Eastern MED is lower because of their reliance on unstable industries like agriculture and oil except Israel (high-tech economy) and Libya (oil wealth but political instability). Consequently, unequal access to water solutions (desalination, recycling) is fueled by GDP disparities, while low-GDP MED countries are caught in a vicious cycle whereby a lack of water results in lower agricultural and industrial output, which in turn leads to slower GDP growth.

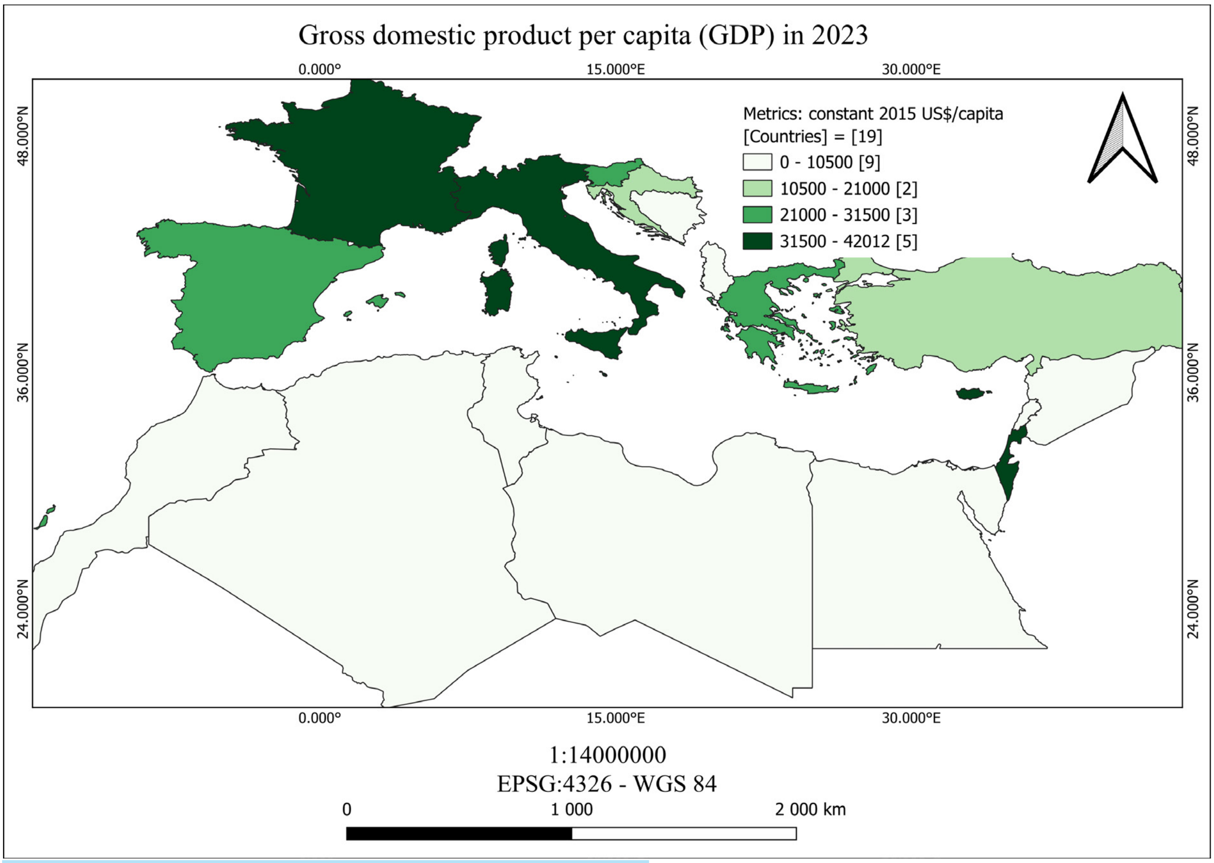



**Figure.5** *Gross domestic product per capita (GDP) in 2023*

Figure 6 indicates that the MED region has a low level of uncertainty, showing that it may have seen a reduction in geopolitical tensions as a result of improved trade relations, the normalisation of Israel-Arab relations, and the ceasefire in Libya. This might lead to more investment in desalination if geopolitical tensions in the MED region are indeed reduced.

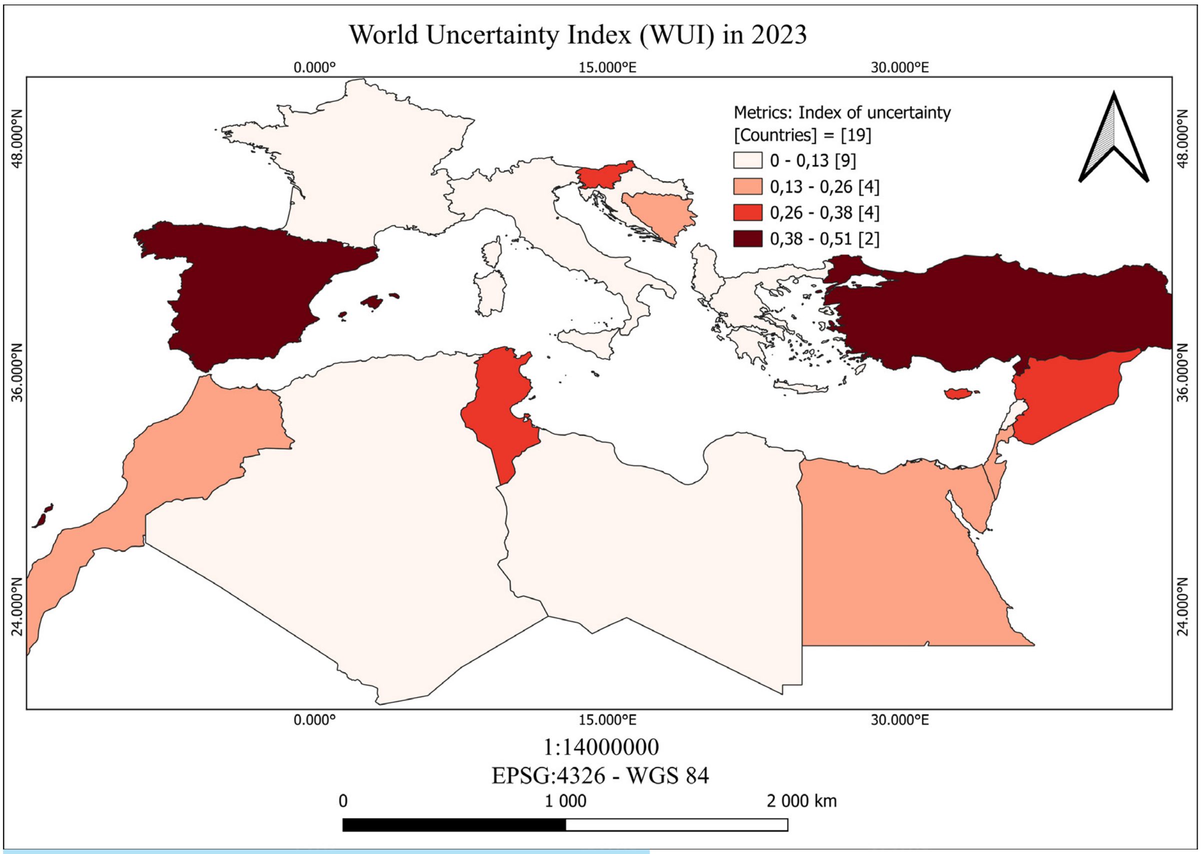



**Figure.6** *World Uncertainty Index (WUI) in 2023*

## *The bivariate local indicators of spatial association*

The following figures indicate BLISA at SL of 10%. The figure 7 shows that SDG-6-WFLK is insignificant for 9 countries, but Slovenia, Croatia, Bosnia and Herzegovina and Greece are among the High-High cluster, confirming that these countries have reached a strong performance of SDG-6 and have rich freshwater resources compared to their population, which lowers the risk of water scarcity. However, Algeria, Tunisia, Libya, Egypt, Israel and Lebanon are among the Low-Low clusters, indicating that these countries are facing severe water stress and scarcity. For instance, Algeria, Tunisia and Libya experience desertification and are dependent on non-renewable fossil groundwater. Egypt has demographic pressure, upstream conflicts with Ethiopia, and a heavy reliance on the Nile River for 95% of its water needs. While Israel and Lebanon are naturally desert countries.

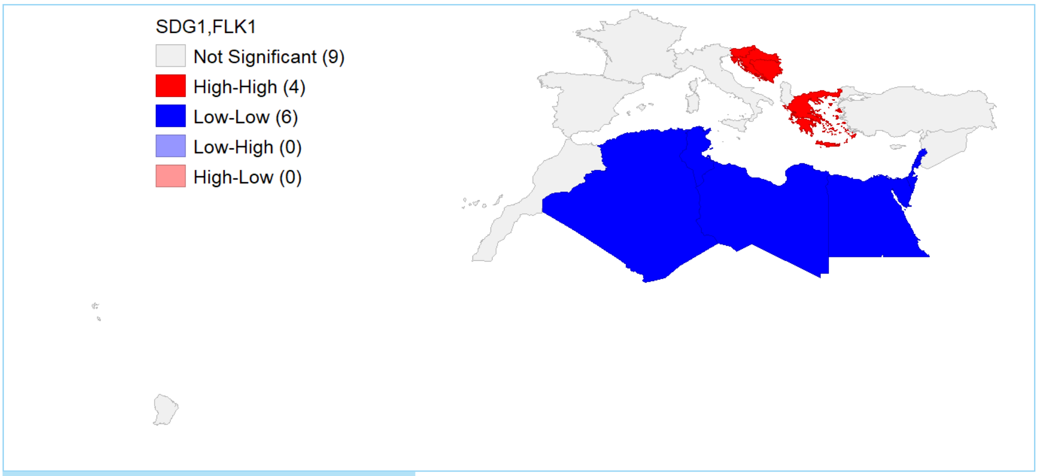



**Figure.7** *BLISA between SDG-6 and WFLK in 2023*

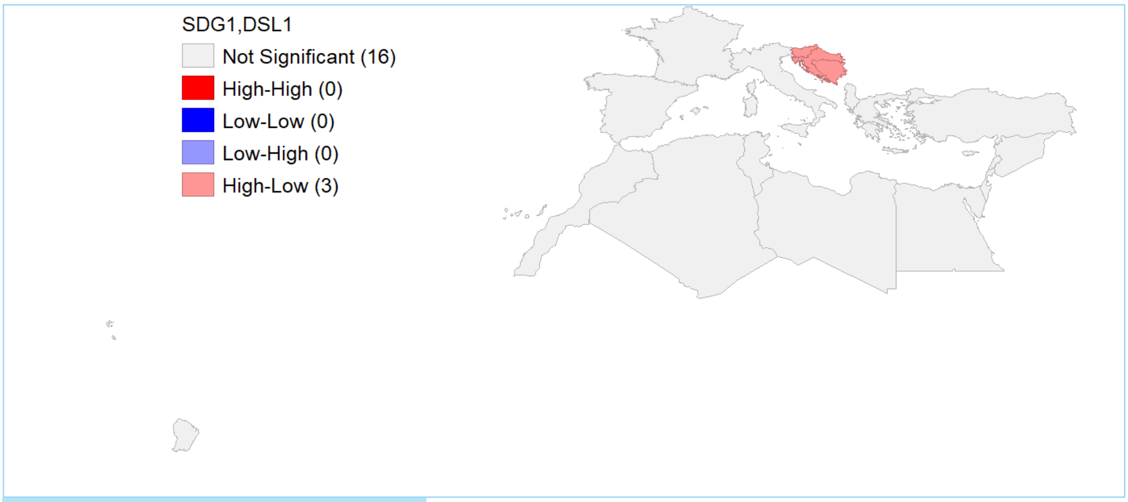



**Figure.8** *BLISA between SDG-6 and WDSL in 2023*

The figure 8 indicates that SDG-6-WDSL is insignificant for 16 countries, but it confirms that Slovenia, Croatia, and Bosnia and Herzegovina are classified as spatial outliers since they are not dependent on desalination and are attaining high levels of SDG-6.

## *The estimation outcomes*

Several results (from table 4 to 7 in appendix section) support the existence of multiple problems in the data (non-stationarity, CSD, and slope heterogeneity), which calls for the application of Machado and Silva's (2019) MMQR procedure, which is better suited in this situation. After completing all the pre-tests required for this study (see appendix section), we use the MMQR procedure to perform the long-run estimation analysis, as shown in table 3.

| Variables | LnSDG | LnSDGW | LnSDGS | LnSDGFR | LnSDGSC |
|---|---|---|---|---|---|
| LnDSL | 0.012***<br>(0) | 0.018***<br>(0) | 0.013***<br>(0) | -0.024***<br>(0) | -0.040***<br>(0) |
| LnFLK | -0.173***<br>(0) | -0.238***<br>(0) | -0.152***<br>(0) | -0.862***<br>(0) | 0.938***<br>(0) |
| LnGHG | -0.042**<br>(0.015 | 0.066***<br>(0.005) | 0.092**<br>(0.01) | 0.199***<br>(0) | 0.517***<br>(0) |
| LnGDP | -0.112***<br>(0.002) | -0.109***<br>(0.002) | 0.092***<br>(0) | -0.099**<br>(0.019) | 0.785***<br>(0) |
| LnWUI | -0.0003<br>(0.837) | -0.0013<br>(0.518) | 0.0033**<br>(0.023) | 0.0077**<br>(0.023) | -0.0084<br>(0.159) |
| Intercept | 1.933***<br>(0) | 2.26***<br>(0) | -0.136<br>(0.673) | 10.11***<br>(0) | -7.047***<br>(0) |
| **Quantiles 25th** | | | | | |
| LnDSL | 0.013***<br>(0) | 0.017***<br>(0) | 0.013***<br>(0) | -0.014**<br>(0.026) | -0.044***<br>(0) |
| LnFLK | -0.199***<br>(0) | -0.245***<br>(0) | -0.177***<br>(0) | -0.968***<br>(0) | 1.194***<br>(0) |
| LnGHG | -0.045*<br>(0.055) | 0.070***<br>(0.003) | 0.060***<br>(0.004) | 0.219***<br>(0) | 0.389***<br>(0) |
| LnGDP | -0.112***<br>(0.002) | -0.092**<br>(0.01) | 0.091***<br>(0) | -0.147***<br>(0.001) | 0.936***<br>(0) |
| LnWUI | -0.0006<br>(0.767) | -0.0018<br>(0.388) | 0.0033*<br>(0.053) | 0.0057<br>(0.129) | -0.0145**<br>(0.023) |
| Intercept | 2.092***<br>(0) | 2.113***<br>(0) | -0.116<br>(0.975) | 11.163***<br>(0) | -10.154***<br>(0) |
| **Quantiles 75th** | | | | | |
| LnDSL | 0.011***<br>(0) | 0.0185***<br>(0) | 0.0126***<br>(0) | -0.034***<br>(0) | -0.037***<br>(0.001) |
| LnFLK | -0.15***<br>(0) | -0.231***<br>(0) | -0.131***<br>(0) | -0.755***<br>(0) | 0.690***<br>(0.001) |
| LnGHG | -0.040**<br>(0.013) | 0.062**<br>(0.041) | 0.034*<br>(0.092) | 0.180***<br>(0) | 0.641***<br>(0) |
| LnGDP | -0.0112***<br>(0) | -0.127***<br>(0.006) | 0.094***<br>(0) | -0.050<br>(0.301) | 0.639***<br>(0) |
| LnWUI | -0.00004<br>(0.975) | -0.0009<br>(0.746) | 0.0033**<br>(0.043) | 0.01**<br>(0.013) | -0.0026<br>(0.702) |
| Intercept | 1.788***<br>(0) | 2.413***<br>(0.002) | -0.241<br>(0.507) | 9.046***<br>(0) | -4.05**<br>(0.048) |

**TABLE 2**

**MMQR estimation**

*Note: "***", '**', '*' refer to the significance level at 1, 5 and 10%. (.) refers to probabilities.*

The findings show that DSL has a positive and significant coefficient at the SL of 1%; a 100% increase will rise SDG or SDG-6, SDGW, and SDGS by 1.2%, 1.8%, and 1.3%, respectively. In the first quantile (quantiles 25th), we find that both SDG-6 and SDGS effects are 0.013 and the SDGW effect is 0.017. In the second quantile (quantiles 75th), SDG-6 and SDGS effects drop to 0.011 and 0.0126, respectively, but SDGW effects rose by 0.0185. However, DSL has a negative and significant impact on SDGFR and SDGSC at the SL of 1%.

FLK has a negative and significant sign at the SL of 1%; a 100% increase will decrease SDG-6, SDGW, SDGS, and SDGFR by 17.3%, 23.8%, 15.2%, and 86.2%, respectively. We find that in the 1st quantile effects, SDG-6, SDGW, SDGS and SDGFR have -0.199, -0.245, -0.177 and -0.968, respectively. In the 2nd quantile, their effects decrease to -0.15, -0.231, -0.131 and -0.755, respectively. However, FLK significantly and positively affects SDGSC, and its quantile effect declined from 1.194 to 0.690.

GHG has a negative and significant coefficient at the SL of 5%; a 100% increase will result in a 4.2% decrease in SDG-6 and no change in the quantile effect. However, GHG has an incredibly positive and significant impact on the rest of endogenous variables at the SL of 1%.

GDP has a negative and significant sign at the SL of 5%; a 100% increase will reduce SDG-6, SDGW and SDGFR by 11.2%, 10.9%, and 9.9%, respectively. While

SDG-6's quantile effect remains constant, SDGW's quantile effect increases from -0.092 to -0.127, while SDGFR's quantile effect decreases from -0.147 to -0.05. However, GDP has a positive and significant impact on SDGS and SDGSC at SL of 5%. While SDGSC's quantile effect declines from 0.936 to 0.639, SDGS's quantile effect stays nearly constant.

WUI has conflicting results, showing a significant and positive impact on SDGS and SDGFR at the SL of 5%, but a negative and insignificant impact on SDG-6, SDGW, and SDGSC.

## DISCUSSION

This study adds to the body of literature by calculating the effects of DSL, FLK, GHG, GDP and WUI on SDG-6 in the selected MED nations. This paper is one of the first to analyse the relationship between SDG-6, DSL, FLK, GHG, GDP, and WUI using a panel econometric framework. Beyond conventional metrics, the paper offers a more comprehensive understanding of water sustainability by utilising SDG-6 and its sub-objectives. Second, few studies include desalination or WUI in SDG-6 models, and the majority only examine climate or economics as single determinants in a cross-section. Third, a more thorough examination of the combined effects of the variables on sustainability is made possible by the paper's integration of several variables into a single panel econometric framework. Prior research has frequently looked at these factors separately or without taking their interactions into account. The paper offers a more nuanced understanding of how these variables interact to influence sustainability by analysing them collectively in a panel context.

The positive impact of desalination shows that in areas with limited water resources, desalination can boost supply, lessen reliance on overfished groundwater or transboundary rivers, and improve water quality in comparison to risky alternatives. This outcome is corroborated by the results of Boyé (2008), and Plan bleu (2024a, 2024b). However, the low DSL value suggests that some countries, like Bosnia and Herzegovina, Croatia, and Slovenia, do not prioritise desalination because they do not require it (high FLK level). Others (France and Italy) are adopting large-scale desalination slowly or cautiously due to its high cost. Others (Cyprus, Algeria, Spain and Malta) are exploring brine treatment technologies to mitigate harm from its expanding seawater desalination sector. Other reasons for this disparity include the fact that some nations prioritise less expensive options (such as surface or groundwater) until a shortage becomes urgent, and that projects may be hampered by poor water governance, a lack of long-term planning, or corruption (Boyé, 2008; Quteishat, 2018).

Integration of renewable energy is essential for a net-positive connexion, and nations must establish policies that promote and subsidise the negative side of desalination (brine) in order to manage it and optimise its benefits. Moreover, it is evident from the quantile effect gap that MED countries have heterogeneous aspects. The impact of desalination is significantly greater in countries (Southern and Eastern MED) with lower SDG-6 and SDGW indexes, as indicated by a decreased value from the first quantile to the second quantile. This shows that targeted investments in desalination projects have a significant impact. However, nations with high SDG-6 and SDGW indexes already benefit less from more desalination due to the fact that they have more diverse water sources or better infrastructure.

The negative effect of FLK indicates that more than half of the MED countries of this study are part of the chronic water stress or scarcity cluster (confirmed in the figure 3). This negative sign is due to regional and national differences, uneven distribution, and a lack of infrastructure in remote places. This outcome is consistent with those of Fader et al. (2020) and the European Commission Joint Research Centre (2025). Moreover, we can attest that the water stress index used here has a number of drawbacks because it ignores infrastructure (such as dams and desalination), seasonal fluctuations, and water quality (Damkjaer and Taylor, 2017). Israel, for example, has a significant level of water stress, but a high level of SDG-6. This paradox results from the nation's need to develop innovative solutions and implement desalination to lessen water scarcity; with the necessary funding and good management, SDG-6 may be accomplished (Ghernaout and Elboughdiri, 2020). However, some others, like Egypt, have limited water resources and fail to meet SDG-6 because they lack resilience and equity. Thus, the detrimental effects of FLK demonstrate that, if institutions are strong, scarcity can encourage innovation, but if nations lack the skills to manage their water resources, abundance does not provide access. Even in situations of physical water stress or scarcity, effective infrastructure and governance can preserve water security by implementing strategies like demand management, desalination, and water recycling (Budds, 2025). Furthermore, a decline in value from the first quantile to the second quantile suggests that FLK has a significant impact on nations with low SDG-6, SDGW, SDGS, and SDGS values. In a country with FLK less than 1,000 $m^3$ per capita and moderate sustainability indicators, this implies that the sensitivity and response to changes in water availability are higher.

The negative impact of GHG demonstrates that the climate change variable does not support the SDG-6 achievement, because GHG causes global warming, which modifies precipitation patterns and exacerbates droughts, both of which lower the amount of freshwater available. This outcome is consistent with the findings of the Intergovernmental Panel on Climate Change (2023), Claro et al. (2024) and Plan Bleu. (2024b). We are aware that the MED is warming 20% more quickly than the rest of the world, which is leading to protracted droughts. River flows, which are essential for agriculture and drinking water, are impacted by the Alps, decreasing snowfall and glacier retreat. By worsening water scarcity, contaminating ecosystems, and forcing nations to rely on fossil fuels for water solutions, GHG and carbon emissions jeopardise SDG-6. Policies that link clean energy (SDG7), water sustainability (SDG-6), and climate action (SDG 13) are needed to address this. Prioritising transboundary water agreements and renewable-powered desalination could change the game for MED countries.

The negative influence of GDP indicates that the economic growth factor does not support the SDG-6 accomplishment. This result is consistent with earlier investigation of Dilekli and Cazcarro (2019). Although wealthier nations often have stronger water infrastructure, there are a number of reasons that can, in some situations, result in a negative GDP-SDG-6 link. Rapid GDP expansion that prioritises water-intensive industries like industrialisation and agriculture can deplete groundwater and increase pollution from untreated industrial discharge (Frone and Frone, 2014). Also, there are disparities in the allocation of water between rural and coastal populations, while putting urbanisation ahead of wastewater and sewage systems and reducing access to sanitation can be another reason behind the negative effect of GDP on SDG-6. Therefore, unsustainable practices that result in inequality, unsustainable growth, and weak institutions may be the cause of such results. Besides, the quantile result shows that countries with higher GDP levels have a significant impact on SDGW, while those with lower GDP levels have a minor impact. This demonstrates that the negative effect is more pronounced in those with higher GDPs, proving that economic growth does not ensure better water outcomes and may even worsen water stress in situations where water resource management is inadequate or polluting industries. However, while nations with lower GDP levels have a major impact on SDGFR, those with higher GDP levels have little effect. Since these lower or middle-income nations frequently have less diversified economies and a greater reliance on basic industries like agriculture, even minor gains or losses in GDP can have a significant impact on SDGFR.

The small, negative, and insignificant effect of WUI shows that some governments and investors postpone or abandon water and sanitation projects because of risk, political unrest, and war (Syria, Lebanon, Egypt and Israel). Lebanon for instance experienced sewage system failure following its economic collapse in 2020, and transboundary water cooperation declined during the pandemic (Nile Dam disputes). Climate uncertainty increases water stress, which frequently peaks during droughts, floods, or food crises, while currency devaluations raise the cost of imported pipes and water treatment chemicals. To ensure long-term stability, nations should take advantage of stable periods to generate money for water projects and encourage cross-border water agreements.

The study has a number of limitations, including missing data for the early years in some countries, which could have skewed the trend. Future studies can include climate events, drought, precipitation, and temperature fluctuations for their analysis. For a more comprehensive perspective and more detailed results, future research should concentrate on comparative analysis between Northern, Southern, and Eastern MED. There are also limitations of the applied technique, including the absence of deep analysis, spatial regression, and causality vs. correlation.

## CONCLUSION

This paper investigates the contribution of DSL, FLK, GHG, GDP and WUI on SDG-6 for 19 MED countries during the period of 2000 to 2023. The outcomes show that DSL has a low, positive, and significant impact on SDG-6, and its two sub-objectives, meaning that desalination represents a good alternative to achieve universal and equitable access to safe and affordable drinking water (SDG-6. 6.1) and the access to adequate and equitable sanitation and hygiene (SDG-6. 6.2). However, DSL has a negative and significant impact on water use and scarcity (SDG-6. 6.4) and the water resources management (SDG-6. 6.5). The second exogenous variable (FLK) has a negative and significant influence on SDG-6, SDG-6W, SDG-6S and SDG-6FR showing that most countries are experiencing a cluster of chronic water stress or scarcity, particularly during periods of significant variation in average annual temperature and precipitation level. WUI, GDP, and GHG all negatively impact SDG-6. Thus, we can validate the first and third hypotheses, which claim that desalination has a positive impact on SDG-6 and that greenhouse gas emissions have a negative one. The second hypothesis, however, cannot be accepted.

The results indicate that although DSL has a positive impact on SDG-6, its contribution is still modest, indicating that increasing the use of renewable energy sources, such as solar and wind, is essential to preventing GHG and carbon emissions from rising. Additionally, FLK undercuts the progress made on SDG-6, indicating that the countries of the Southern and Eastern MED are especially vulnerable and need unconventional water management methods (e.g., desalination and wastewater reuse). Increased GHG emissions strain energy-water nexuses (such as fossil fuel-powered desalination) and deteriorate water quality (SDG.6.3). The negative impact of GDP indicates that equitable investment and improved governance are required to ensure water sustainability. The detrimental and insignificant effect of WUI suggests that economic and political instability impede the advancement of SDG-6 by upsetting water infrastructure projects.

# SUSTAINABILITY IN DESALINATION: ADDRESSING RISKS AND MITIGATION STRATEGIES ACROSS THE MEDITERRANEAN REGION

AUTHOR : MOHAMMED N. ASSAF


Desalinated water reservoir © tifonimages


## Abstract

Desalination has become an increasingly vital solution for addressing water scarcity in the Mediterranean region, yet it brings with it a range of environmental and social challenges. This study evaluates expert perceptions of desalination impacts and mitigation priorities across six Mediterranean countries: Spain, Greece, Israel, Libya, Algeria, and Tunisia. Using an integrated approach that combines Failure Mode and Effect Analysis (FMEA) with the Analytical Hierarchy Process (AHP), the study offers a structured and comparative assessment of six impact categories, spanning environmental, health, and socio-economic dimensions, and six corresponding mitigation strategies. Results reveal that energy and climate risks, social risks, and marine ecosystem damage are the most significant concerns, though their prioritisation differs significantly between countries depending on factors such as governance capacity, public awareness, coastal vulnerability, and energy reliance. Energy use mitigation, site selection, and social mitigation strategies are consistently ranked as the most effective responses. The findings highlight the need for tailored, country-specific approaches that address both environmental and socio-political dimensions of desalination, while calling for stronger regional collaboration to support sustainable water solutions across the Mediterranean basin.

## INTRODUCTION

Water shortage is one of the most significant challenges facing countries in the Mediterranean basin. Although large quantities of water are available in seas and oceans, they are not suitable for drinking or human use due to their high salinity. The Earth's total freshwater resource consists of surface freshwater which represents less than 1% of the available water according to Mishra, (2023). In addition to insufficient water resources, these resources are increasingly threatened by depletion due to climate change and human activities such as industrial and economic development, population growth, and over-exploitation (Darre and Toor, 2018; Teow and Mohammad, 2019). The classification of water resources splits between natural (conventional) and non-conventional sources. Conventional water resources divide into freshwater and saline water based on their salt concentrations. The freshwater supply exists above ground in rivers and lakes and underground where salinity levels remain low and natural water cycles maintain its constant renewal. In between freshwater and seawater, brackish waters, found in estuaries, deltas, and coastal aquifers, represent transitional water sources with highly variable salinity levels influenced by both marine and freshwater inputs. Surface water from freshwater lakes and rivers contains minimal salt content which enables easy suitability for drinking purposes. Underground water reservoirs store fresh groundwater that maintains slightly elevated salinity levels than surface freshwater according to Mickley (2006). According to Gleick (2006) this groundwater represents 0.76% of global water while being responsible for 30% of existing freshwater resources. Earth's freshwater reserve consists predominantly of inaccessible glacier and permanent snowfield water that amounts to 69% of the total freshwater on the planet. Saline water represents the largest portion of Earth's water supply since it includes oceans, seas and saltwater lakes amounting to 97.5% according to Gleick (2006). In comparison, the Mediterranean basin's total renewable freshwater resources amount to approximately 550 km³ per year, representing just about 1.2% of the world's renewable water resources. These resources are unevenly distributed across the region: around 50% are concentrated in Italy and Greece, about 25% in catchments located in France and Turkey, while catchments on the southern and eastern rims of the basin provide only 4% and 2%, respectively (FAO, 2010).

Desalination stands as an increasingly popular solution to convert saline water into freshwater since freshwater remains scarce and difficult to access. Desalination is the process of producing fresh water from salty water sources such as seawater or brackish water. Since its development in the 1950s, desalination has become an increasingly reliable method of water supply, benefiting from advances in technology and improved cost-effectiveness. Globally, the capacity for desalination has significantly expanded. In 2005, global capacity was roughly 35 million cubic meters per day (MCM/day) (Gleick, 2006), but this number had risen to approximately 110 MCM/day by 2023. Of this total, about 62.25% was utilized for municipal water supplies, and approximately 30.2% served industrial uses (Jones et al., 2019). In the Mediterranean region, desalinated water production has experienced significant growth, with capacity increasing by approximately 446.8%, from 940,842 m³/day to 5,144,441 m³/day, over the last decade. This represents nearly 4.7% of global desalination capacity as of 2023 (Plan Bleu, 2024). Similar to global trends, the majority of desalinated water in the Mediterranean is supplied to municipalities, particularly in water-scarce countries such as Israel, Spain, and Algeria, where municipal supply dominates demand.
Various elements are pushing the worldwide expansion of desalination facilities. The rapid expansion of population combined with changed precipitation patterns from climate total freshwater resource available change and improved technology for energy usage reduction has led numerous countries with scarce water supply to use desalination as a supplemental water source. The Mediterranean region, particularly the southern Mediterranean, is among the areas most vulnerable to water scarcity and low per capita water availability (Mastrocicco and Colombani, 2021). Several countries in this region fall well below the threshold of 1,000 m³ of renewable freshwater resources per capita per year with nations such as Libya, Algeria, and Malta reporting levels under 500 m³/year (Blinda and Thivet 2009). These challenges have made the search for alternative water sources essential. Consequently, desalination has emerged as one of the most viable processes, providing a reliable and effective solution to meet the water needs of both human and industrial uses (Mavukkandy et al., 2019; Panagopoulos et al., 2019). According to the International Desalination Association (IDA), there are approximately 20,000 desalination plants worldwide. Around 7.3% of these plants are located in the Mediterranean region, with a combined daily desalination capacity of about 15.6 million cubic meters. Projections suggest that by 2030, the desalination capacity in the Mediterranean could increase to approximately 30–40 million cubic meters per day (International Desalination Association, 2019).

In fact, desalination presents a number of benefits and risks. The primary benefit is a sustainable supply of drinking water. However, there are potential environmental, socio-economic, and health impacts that must be addressed (Areiqat and Mohamed, 2005; Miller et al., 2015; Roberts et al., 2010; Sadhwani et al., 2005; Shemer and Semiat, 2017; Tularam and Ilahee, 2007). These impacts include the discharge of brine with extremely high salinity levels containing hazardous chemicals, greenhouse gas (GHG) emissions, thermal and noise pollution, as well as high energy consumption, significant solid waste, and degradation of marine ecosystems. To mitigate these impacts, several technologies, strategies, and measures have been developed and adopted. These solutions include green desalination technologies such as renewable energy, hybrid desalination, water channels, and energy recovery. Additionally, strategies to alleviate environmental adverse effects include brine discharge treatments, carbon sequestration, brine mining, and careful intake and outfall design.

Many previous studies have examined the potential impacts and risks of desalination. However, the environmental impact of desalination can vary significantly between countries and more local scales, largely due to differences in geography features (topography, bathymetry), natural hydrological patterns, technology used, regulatory frameworks, and environmental sensitivities of the related species. The same variability applies to strategies and actions for mitigating environmental impacts. Therefore, this study aims to assess the potential impacts of desalination plants at the country level and to evaluate strategies and measures to enhance the sustainability of this technology.

## METHODOLOGY

This study identifies the potential risks of desalination on the environment, with the ultimate goal of achieving resilience to desalination and the efficient management of this sector. A structured questionnaire was used as the main data collection instrument to determine the environmental and social effects of desalination and appropriate mitigation measures to be adopted. The survey was designed following a two-step process. The initial step was an extensive literature review, which was based on a review of over 40 peer-reviewed scientific articles, policy reports, and technical documents of 2000-2025. The literature covered key thematic areas including brine discharge and marine ecosystem damage, energy consumption and carbon emissions, groundwater contamination, social acceptance and public perception, site selection challenges, health risks related to chemical residues, and emerging mitigation technologies such as renewable-powered desalination and brine management solutions. The review assisted in identifying the most frequently reported environmental and socio-economic effects related to desalination and the related mitigation and adaptation measures. Second, focus group discussions were conducted with a small group of academic and professional experts in desalination and water policy to validate the relevance and clarity of the selected variables.

The survey targets desalination experts in six Mediterranean countries, Spain, Greece, Israel, Libya, Algeria, and Tunisia. To obtain a broader perspective, experts were chosen from different fields related to desalination to reflect their knowledge and experience. Involving a diverse group of experts was essential to ensure a comprehensive view of the potential impacts of desalination on the environment. The survey was structured in two parts. The first part asked the experts to rate the potential impacts of the desalination risk factors on the different sectors in their countries. The second part asked them to evaluate the effectiveness of the proposed mitigation/adaptation strategies. An expert judgment was recorded using a semi-quantitative scoring system; the entire description of this scoring system is provided in the subsequent sections. To analyze the collected data, Failure Mode and Effect Analysis (FMEA) were integrated with the Analytical Hierarchy Process (AHP) multi-criterion decision-making approach to evaluate the desalination risk factors and recommend a best set of adaptation strategies. FMEA systematically identified possible risks in the different sectors and provided a structured means to rank the severity , occurrence, and detectability of each risk (Table 1). The AHP was then employed to rank the areas of significant concern to the experts and summarize their overall view of the likelihood of success of the corrective actions or strategies that could be used in response to the risk factors. A multi-criterion decision-making approach based on pair-wise comparisons was then used to evaluate the adaptation strategies feasible in the Mediterranean context.

While all listed sub-criteria contribute significantly to their respective impact categories, the relative weight or importance of each can vary depending on local environmental sensitivity, technological configurations, and site-specific factors. For instance, within the 'Marine Ecosystem Damage' category, biodiversity loss resulting from entrainment, impingement, and brine discharge is often considered more immediately disruptive than habitat destruction caused by high salinity or temperature, as it directly affects population dynamics and food webs. However, long-term habitat degradation may have more persistent and less reversible consequences. The survey design allowed experts to consider such trade-offs through structured scoring in the FMEA–AHP framework, detailed in the following sections.

| Desalination Impacts (Main Criteria) | Problems caused by Desalination Impact (sub-criteria) |
|---|---|
| Marine Ecosystem Damage (Water intakes & Brine discharges) | Biodiversity loss from entrainment, impingement, and brine discharge |
| | Habitat destruction due to high salinity, temperature, and chemicals. |
| | Disruption of marine food chains affecting fisheries and marine ecosystems |
| | Seabed pollution and increased bioaccumulation risks |
| | Seagrass loss impacts carbon sequestration and marine habitats |
| Groundwater Risks | Brine seepage contaminates groundwater with high salinity and chemicals. |
| | Over-extraction lowers water tables, reducing freshwater availability. |
| | Soil degradation from increased salinity, harming agriculture. |
| Water and Air Pollution | Increased turbidity and sediment suspension reduce water quality. |
| | Waste biomass from intake screens pollutes marine waters. |
| | Air pollution from desalination emissions. |
| Energy and Climate Risks | High energy demand increases carbon footprint. |
| | GHG emissions accelerate climate change. |
| | Waste heat discharge affects coastal environments. |
| | Rising operational expenditures (OPEX) due to energy-intensive operations & carbon taxes |
| Health Risks | Bioaccumulation of heavy metals in seafood. |
| | Air pollution exposure affects respiratory health. |
| | Chemical residues in desalinated water raise long-term health concerns. |
| Social and Economic Risks | Noise pollution affecting nearby communities. |
| | High Capital Expenditures (CAPEX) for plant construction and infrastructure. |
| | Decline of coastal tourism due to environmental degradation. |
| | Fisheries loss from reduced fish populations, causing unemployment and need for social subsidies. |
| | Need for substantial subsidies or tariffs to keep desalinated water affordable. |

**TABLE 1**
**Desalination impacts and the associated problems**

## *Failure Mode and Effects Analysis*

FMEA is a systematic method for evaluating the impact of potential risks by assessing their severity, occurrence probability, and detectability 24.(Schneider, 1996). It calculates a Risk Priority Number (RPN), which serves as a criticality rank, using the following formula:

$$RPN = S \times P \times D, \qquad (1)$$

where S represents the severity of a failure, P is the probability of its occurrence, and D is the detectability of the failure. In the traditional application of FMEA, an integer scale ranging from 1 to 10 is utilized to assess these three risk factors. Failure modes that yield higher RPNs are generally considered to be of greater significance and are thus prioritized for corrective action.

In the context of assessing desalination impacts on the environment, 'severity' relates to the extent of an impact's end effect. A higher severity value is assigned to more significant consequences of desalination. 'Probability' denotes the likelihood of desalination impacts occurring, while 'detectability' refers to the ability to foresee these impacts before their occurrence.

## *Analytic Hierarchy Process*

The AHP, a key component of multi-criteria decision analysis, provides a structured approach for framing decision problems and evaluating and ranking various alternatives. AHP is a widely used technique for ensuring decision-making quality through pairwise comparison. This method has been applied in the current research study.

The AHP equips researchers with a hierarchical framework to analyze problems and integrate decision-makers' experiences into the evaluation process. The hierarchy starts with the main objective at the top, followed by criteria, sub-criteria (if applicable), and potential solutions or alternatives. The process involves assigning weights to these criteria and sub-criteria to facilitate the comparison of alternatives. Pairwise comparisons are then conducted using a scale from 1 (indicating indifference) to 9 (indicating high preference). The AHP pairwise comparison scale, as outlined by (Wind and Saaty,1980), is shown in Table 2.

| Intensity of importance | Scale of importance |
|---|---|
| 1 | Equal risk to the two criteria |
| 3 | Low risk of one criterion compared to another |
| 5 | High risk of one criterion compared to another |
| 7 | Very high risk of one criterion over another |
| 9 | Extremely high risk of one criterion over another |
| 2,4,6,8 | Intermediate values |

**TABLE 2**
**AHP pairwise comparison scale (Wind and Saaty,1980)**

The relative importance of different parameters is calculated using the RPN values from Equation (1), as shown in Equation (2):

$$a_{ij} = (c_i - c_j)\frac{c_{max} - c_{min}}{9} \qquad (2)$$

Where, $a_{ij}$ represents the importance of the $i_{th}$ parameter relative to the $j_{th}$ factor.

$C_i$-$C_j$ represents the difference between the RPN scores of the $i_{th}$ and $j_{th}$ factors, and $C_{min}$ and $C_{max}$ are the overall minimum and maximum RPN scores, respectively.

The basic steps of the AHP include defining the problem and decomposing it into a hierarchical structure, creating pairwise comparison matrices, evaluating the consistency index, and synthesizing the hierarchy to rank alternatives.

### *Adaptation strategies*

To address the challenges posed by desalination to the environment, six key solutions have been identified through an extensive literature review. The aim is to apply these in the desalination sector to boost resilience. Each proposed solution was evaluated and then ranked based on its relative in combating the impact of the environment by experts. To this end, we used the AHP, as outlined above, with a qualitative scale ranging from 1 (least effective) to 9 (most effective). The strategies are:

1. Source Water Intake Mitigation
2. Brine Discharge Mitigation
3. Energy Use Mitigation
4. Site Selection
5. Socio-Economic & Community-Based Mitigation Strategies
6. Integrated Water Resource Management

A detailed description of each strategy, including technical measures and application contexts, is provided in Annex 1.

## RESULTS AND DISCUSSION

This study is based on expert inputs gathered from six Mediterranean countries, ensuring a diverse and context-specific understanding of desalination impacts and mitigation strategies. These participants brought a range of expertise in water management, environmental policy, and engineering, providing valuable insights into both the technical and social dimensions of desalination in their respective national contexts. Their assessments form the foundation of the comparative analysis is presented in the following sections. A summary table showing how each country rated the different impact sub-criteria is included in Annex 2 (see Table A2). It helps provide a clear basis for comparing expert views across the six Mediterranean contexts.

### *Spain*

Social risks stand as the most important impact of desalination in Spain according to results analysis with a relative weight of 0.43 (Figure 1.a). The study demonstrates that social factors have become crucial elements in securing community acceptance and addressing equity issues during the operation of desalination plants. Desalination raises concerns among communities because it appears to provide better benefits to tourism and agribusiness sectors at the expense of local water needs and increased prices for water services. This issue gains importance in environmental justice and social equity debates. Within this category, High Capital Expenditures (CAPEX) for plant construction and infrastructure' carries the highest weight (0.56), indicating financial and economic barriers as the most pressing social concern, followed by the need for subsidies to keep desalinated water affordable (0.39).

Energy and climate risks emerged as the second most important concern (0.217) due to increasing recognition of environmental consequences from energy-intensive desalination processes. Spain's efforts to merge renewable energy into its power network have progressed notably but desalination facilities continue to generate environmental concerns about their carbon emissions which becomes significant when analysing long-term sustainability and EU climate policy requirements. The research indicates that desalination requires immediate attention for energy-saving technological advancements and the exploration of low-carbon methods to maintain its function as a climate-resistant solution. The most heavily weighted sub-impact in this category is 'High energy demand increasing carbon footprint' (0.29), closely followed by 'GHG emissions accelerating climate change' (0.27).

The study participants evaluated groundwater risks and marine ecosystem damage as moderately important issues (0.148 and 0.129 respectively). Spain has depended on desalination plants located both near the coast and inland throughout its history, yet practical environmental risks persist including brine damage to ocean ecosystems and localized water extraction issues which could lead to water salinization. Their lower ranking than social and energy-related impacts demonstrate an existing trust in current environmental regulations and mitigation practices implemented in Spain.  According to Sola et al. (2020), the Spanish experience offers a "comprehensive approach for minimizing the potential environmental impacts of brine discharge that can be applied in regions where desalination practices are under development." The combination of strong regulatory oversight, continuous research, and corrective action when impacts are identified has allowed Spain's desalination sector to expand without causing significant harm to marine environments. Under marine ecosystem damage, 'Biodiversity loss from entrainment, impingement, and brine discharge' received the highest sub-criteria weight (0.45), followed by 'Seagrass loss impacts carbon sequestration and marine habitats' (0.24).

In the case of groundwater risks, 'Over-extraction lowering water tables' stands out as the primary concern (0.66), while 'brine seepage contaminating groundwater' follows at 0.24.

Health risks (0.039) and water and air pollution (0.037) receive limited consideration because the country maintains robust water quality regulations coupled with strict drinking water standards along with desalinated water treatment protocols for compliance verification. Among health concerns, the most cited sub-impact was 'Chemical residues in desalinated water raising long-term health concerns' (0.43), while 'bioaccumulation of heavy metals in seafood' and 'air pollution exposure affecting respiratory health' followed with weights of 0.33 and 0.24, respectively.

The study reveals site selection stands as the primary mitigation approach (0.212) in Spain because proper plant installation helps reduce environmental issues and social disputes. Energy use mitigation stands at 0.189 in the ranking due to rising interest in reducing desalination carbon emissions and following Spain's climate policy objectives. The analysis indicates Integrated Water Resource Management (0.174) and social mitigation strategies (0.167) occupy subsequent positions due to their importance in complete planning and stakeholder collaboration. The identified priorities align with previous studies which demonstrated that social risks created the most substantial impacts from desalination. The implementation of brine discharge mitigation (0.137) and source water intake mitigation (0.121) received lower priority due to Spain's strong regulatory frameworks and existing technical solutions.

Overall, the results suggest that while technical fixes remain important, successful desalination increasingly relies on strategic planning, public trust, and energy sustainability.

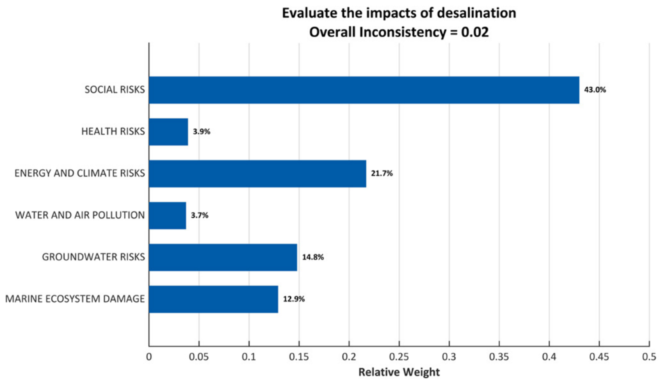



**Figure.1** *(a) Relative weights of desalination impacts in Spain.*

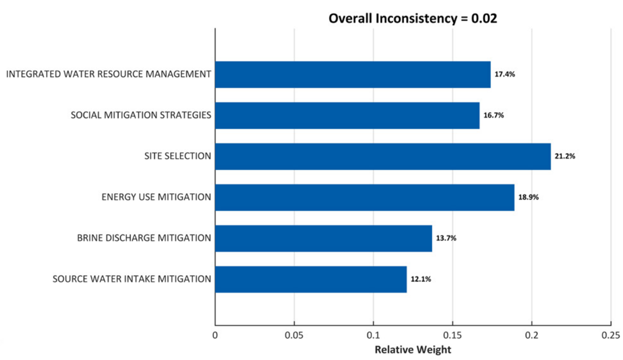



**Figure.1** *(b) Evaluation of mitigation strategies to address desalination impacts.*

### *Greece*

The assessment of desalination impacts in Greece shows that energy and climate risks hold the most significant weight at 0.539 (Figure 2.a). The high level of concern stems from ongoing energy sustainability problems and the economic strain of energy-intensive infrastructure throughout Greece. The high importance Greece places on energy and climate risks regarding desalination demands immediate research into renewable-powered desalination systems. Within this category, 'High energy demand increasing carbon footprint' received the highest weight (0.33), followed by 'Rising operational expenditures (OPEX)' (0.29), while 'GHG emissions' and 'waste heat discharge' were both moderately weighted (0.19 each).

The second most crucial risk factor for groundwater protection is 0.205 which corresponds to the persistent problems of over-extraction and saltwater intrusion that affect coastal and island areas. The implementation of desalination systems to combat water scarcity needs proper management to prevent worsening conditions in local water systems. The findings emphasize how water scarcity solutions need to maintain equilibrium between resource conservation and water scarcity solutions. In this category, 'Over-extraction lowering water tables' was the dominant concern (0.53), followed by 'brine seepage contaminating groundwater' (0.33).

Social risks exhibit an average importance level of 0.111 in the evaluation. The challenges Greece faces with its infrastructure and environmental issues surpass the need for public support and stakeholder participation in desalination projects. Key social concerns include the need for substantial subsidies or tariffs (0.37) and high capital expenditures (0.35), while other issues like coastal tourism decline (0.11) and fisheries loss (0.03) were of lesser concern. Perceptions from experts indicate that health risks along with marine ecosystem damage and water and air pollution rank lower in importance than other factors (0.049 ,0.047 and 0.048 respectively). This suggests these concerns either present no immediate threat or can be managed through existing regulatory measures. The smaller dimensions of Greek desalination facilities, particularly those located on islands, might lead people to believe their environmental and health effects remain within manageable local boundaries. Among marine ecosystem risks, 'Biodiversity loss from entrainment and brine discharge' was the most emphasized (0.30), while other concerns—habitat destruction, seabed pollution, and seagrass loss—were evenly weighted (0.20 each).

The Greek mitigation strategy evaluation demonstrates that Energy use mitigation stands out as the most important measure (0.222) because desalination technology consumes substantial energy resources in off-grid island regions. These regions typically rely on diesel-powered electricity generation, leading to elevated operational costs and significant greenhouse gas emissions. The research findings align with previous results which identified energy and climate risks as Greece's most critical desalination consequences. Site selection stands as the second most important factor (0.216) since many Greek coastal areas and islands exist in regions with sensitive marine ecosystems or locations that have already experienced tourism and development impacts. Plant location decisions must be prioritized since they determine both ecological protection outcomes and efficient system deployment. The ranking of Integrated Water Resource Management (0.178) shows that Greek stakeholders endorse an organized approach to link water management objectives with overall desalination activities. IWRM represents an essential framework for Greece to optimize its water use and secure long-term sustainability because it addresses the seasonal water availability challenges and the governance gaps between mainland and island territories. The importance of strategies to address social effects (0.141) and brine discharge management (0.14) was deemed moderate because of their continued focus on social and environmental considerations although these areas may be viewed as easier to control. The acceptance of small desalination projects by public audiences remains crucial but Greek communities tend to show less resistance to these facilities since they understand the value of dependable freshwater supplies. The ranking of source water intake mitigation strategies came in last with 0.103 because Greek desalination units mostly have smaller sizes while demonstrating good performance in their intake designs.

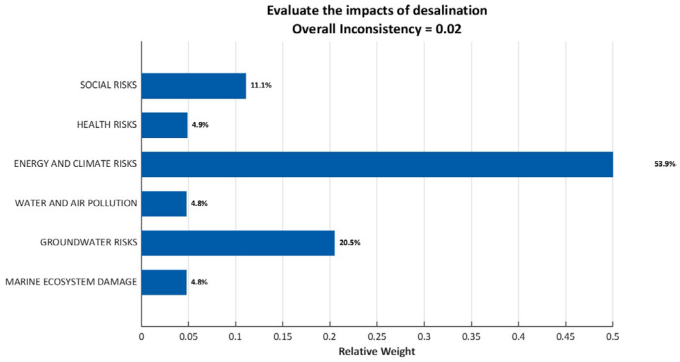



**Figure.2** *(a) Relative weights of desalination impacts in Greece.*

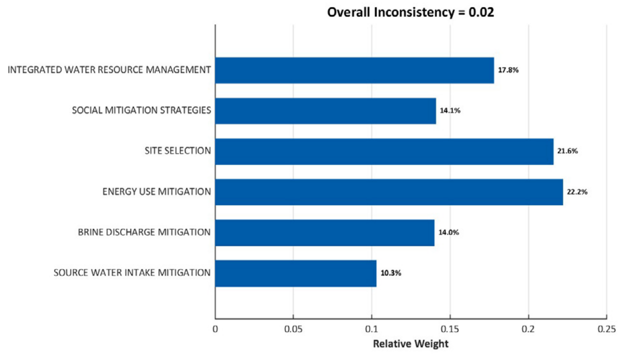



**Figure.2** *(b) Evaluation of mitigation strategies to address desalination impacts.*

## *Israel*

The result from Israel indicates that energy and climate risks related to desalination were evaluated as the most important risks with a weight of 0.499 (Figure 3.a). Israel places a strong emphasis on desalination because it serves as the main source to provide water for its national requirements (Tal, 2018). Despite that Israel's plants are highly energy-efficient by world standards, it produces most of its desalinated water through conventional power sources. Despite ongoing projects to boost energy efficiency along with renewable integration because this practice results in greenhouse gas emissions that counter climate commitments. Israel faces an immediate requirement to boost sustainability within its desalination sector because water requirements are expanding. Within this category, 'High energy demand increasing carbon footprint' was the most heavily weighted sub-impact (0.38), followed by 'Rising OPEX due to energy use and carbon taxes' (0.29), 'Waste heat discharge' (0.19), and 'GHG emissions' (0.14).

Marine ecosystem damage emerged as the second major concern for stakeholders at 0.287 on a scale from 0 to 1. This indicates the environmental challenges associated with building coastal desalination facilities. Thermal and saline pollution from brine discharges threatens the sensitive marine habitats located along Israel's Mediterranean coast. The country has adopted state-of-the-art brine dispersion systems, but the environmental impacts of continuous brine exposure still present a major concern (Kenigsberg et al., 2020). The assessment takes into account the total environmental pressure that desalination facilities create because they operate near one another within concentrated areas. The main sub-criteria under this category were 'Biodiversity loss from entrainment, impingement, and brine discharge' (0.30), followed by 'Seagrass loss' (0.25), 'Habitat destruction from salinity, temperature, and chemicals' (0.20), 'Seabed pollution and bioaccumulation' (0.20), and 'Disruption of marine food chains' (0.05).

The rating system assigned similar weight to social risks, health risks, water and air pollution, and groundwater risks which received equal weight at 0.052–0.055. This reflects the perception that these issues are largely under control in Israel, supported by strict environmental regulations, long-term monitoring, and advanced intake and filtration technologies. Environmental effects such as turbidity and biomass accumulation have been shown to be localized and minimal, posing low ecological risk near intake and discharge zones.. The relatively low concern for groundwater risks among Israeli respondents can be attributed to the country's limited reliance on groundwater for brine disposal, as most desalination plants discharge brine directly into the sea. Also, desalination has also contributed to aquifer recovery by decreasing the need for over-extraction, thereby enhancing groundwater protection. The low social risk weight stems from public support for desalination as a national solution because the country has a long history of desalination success combined with its integration of desalinated water in domestic, agricultural and industrial supply. The existence of robust regulatory systems seems to account for the minimal public concern about health risks and pollution effects. Israeli mitigation strategy assessment displays a strategic method for effectively handling the main issues stemming from desalination processes. The selection of proper site locations (0.209) and strategies to reduce energy usage (0.208) became the leading priorities because Israel wants to protect its environment and minimize its desalination energy consumption. Strategic decisions about site selection in Israel become essential because the country depends on large-scale desalination plants, with average capacity of 500 MCM/year (Kramer et al. (2022)), to supply water while operating in a dense coastal environment. The energy efficiency of desalination continues to be a crucial priority for the country because of its growing focus on minimizing the environmental impact of power consumption. The importance of Integrated Water Resource Management (IWRM) stands at 0.173 showing Israel's ongoing dedication to complete water resource management. Israel operates its water sector as one integrated system with desalination serving alongside wastewater reuse and aquifer recharge and national distribution networks. IWRM enables desalination to work with other water elements through a harmonious integration which leads to improved sustainability and resilience. The assessment of brine discharge mitigation stands at 0.145 because marine environmental health concerns continue to rise as multiple desalination plants operate in the same areas. Israel implements an advanced brine management system, yet the total environmental effects of the Mediterranean ecosystem remain critical for continued monitoring and enhancement. He received the least priority at scores of 0.134 and 0.131 respectively. People in Israel support desalination operations because the technology provides essential protection for their national water supply. The existing social concerns about desalination have limited impact on public perception because of widespread acceptance of the technology. The management of source water intake seems to be considered a technical problem that people can handle because of common practices such as subsurface or screened intakes.

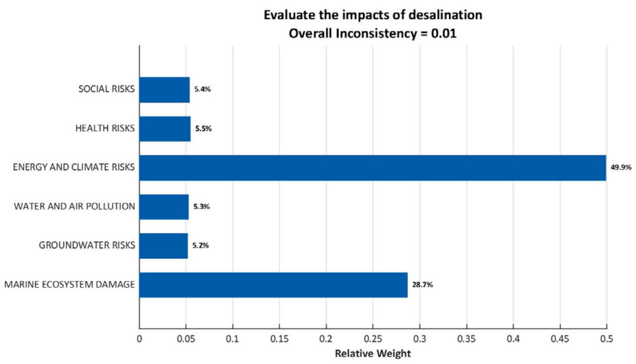



**Figure.3** *(a) Relative weights of desalination impacts in Israel.*

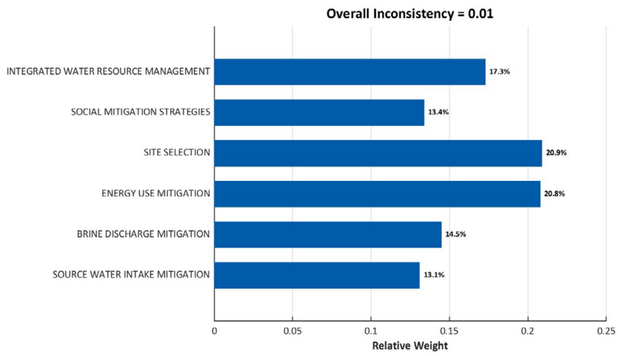



**Figure.3** *(b) Evaluation of mitigation strategies to address desalination impacts.*

## *Libya*

The overall weight of energy and climate risks together with social risks reaches almost 60% in the evaluation of desalination in Libya. The country's unstable and limited energy infrastructure drives the high relative weight of 0.345 for energy and climate risks. Libya experiences numerous power blackouts and fuel scarcity in different areas which creates severe challenges due to desalination plants' energy-intensive operations. The absence of renewable energy technologies combined with fossil fuel dependence increases financial and environmental burdens on the country. Within this category, 'High energy demand increasing carbon footprint' (0.37) and 'GHG emissions' (0.31) are the dominant concerns, while 'rising OPEX from energy operations and carbon taxes' follows with 0.21, and 'waste heat discharge' is rated lowest at 0.11. Social risks stand as the second most important element at 0.25. Large-scale infrastructure implementation within this context faces challenges due to weak public services and fragmented governance structures and low institutional trust levels. The social aspects of desalination projects become more sensitive because of concerns about water affordability and distribution fairness as well as possible discrimination affecting rural communities. Libya's public acceptance depends on environmental results as well as how fairly and transparently the water management choices are made. In addition, economic sustainability plays a major role in shaping social perceptions of desalination. Desalinated water is significantly more expensive than conventional sources such as rivers or aquifers. In Libya, where water has traditionally been provided either for free (via the Great Man-Made River) or at very low subsidized tariffs, desalination introduces a high-cost water source into the system. Studies estimate that the unit cost of desalinated water can range from \$0.5 to \$1.3 per cubic meter for large seawater plants, depending on energy **prices and plant ef**ficiency (Kotagama et al. (2016)), with some plants reporting average costs as high as \$2.69/$m^3$ due to high fuel costs and operational inefficiencies (Ashour and Ghurbal 2004). In contrast, the price charged to Libyan consumers remains extremely low, about \$0.10–\$0.20/$m^3$, due to substantial government subsidies (UNICEF 2022). A UNICEF report found Libya's average municipal tariff to be just \$0.15/$m^3$, only

20% of the MENA regional average and far below the real cost of production (UNICEF 2022). This large gap implies that the government bears most of the financial burden, resulting in substantial annual subsidies to support desalination, covering fuel, maintenance, and capital investment. These structural inequalities and fiscal pressures amplify public sensitivity toward water equity, further complicating social acceptance of desalination projects. Within the social category, the most significant sub-issues were 'need for substantial subsidies or tariffs to keep desalinated water affordable' (0.46) and 'high CAPEX for infrastructure' (0.38). In contrast, noise pollution (0.08), coastal tourism decline (0.06), and fisheries loss (0.02) were considered minor concerns. The damage to marine ecosystems stands as a significant concern with a rating of 0.191 since Libya possesses an extensive coastal region along the Mediterranean. The limited environmental regulations with weak monitoring capabilities in certain regions lead to severe damage of coastal marine biodiversity and fisheries when concentrated brine is discharged into ocean waters. This poses substantial economic and cultural threats to coastal communities. In this category, the most impactful sub-criteria were 'biodiversity loss from entrainment, impingement, and brine discharge' (0.37) and 'habitat destruction due to high salinity, temperature, and chemicals' (0.36). Other sub-issues like disruption of marine food chains (0.11), seagrass loss (0.11), and seabed pollution (0.06) were rated lower.

In Libya, energy use mitigation and site selection are top priorities for desalination, reflecting concerns over unstable energy supply and the environmental sensitivity of coastal zones. In Libya, the scarcity of environmentally suitable and socially acceptable locations, coupled with infrastructure constraints, makes site selection a critical decision point for mitigating both ecological and community-level risks. Social mitigation strategies are also emphasized, highlighting the need for public trust and equitable access. Brine discharge mitigation is moderately important, while IWRM and intake mitigation are lower priorities, possibly due to limited institutional capacity. This may reflect Libya's limited integration of water management sectors and the absence of a centralized governance framework to coordinate desalination with broader water reuse, aquifer recharge, or long-term planning. Overall, the focus is on practical, high-impact measures that address both technical and social vulnerabilities in a fragile context.

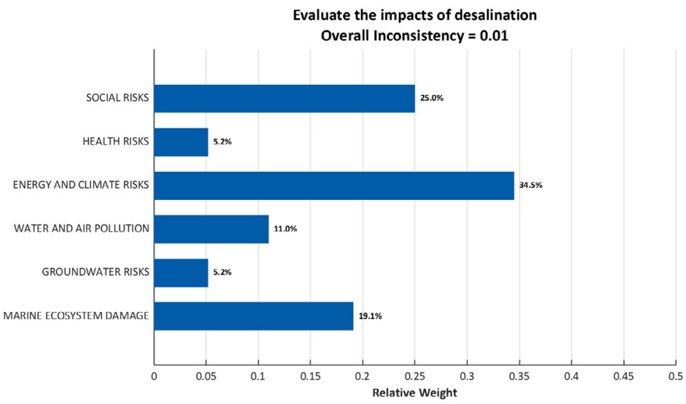



**Figure.4** *(a) Relative weights of desalination impacts in Libya.*

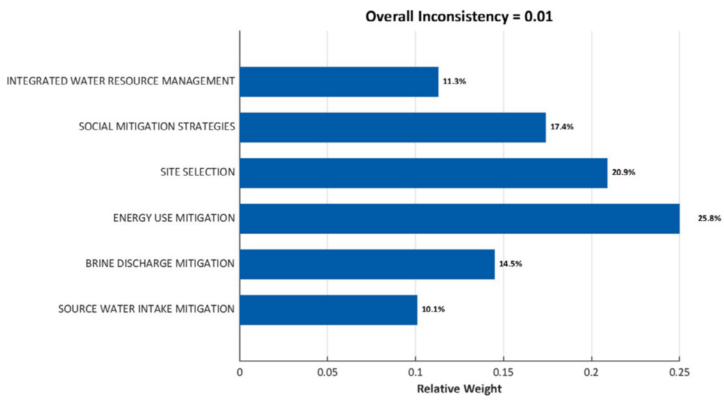



**Figure.4** *(b) Evaluation of mitigation strategies to address desalination impacts.*

## *Algeria*

The evaluation of desalination impacts in Algeria highlights a strong concern for both energy and climate risks and social risks, which together account for over half of the total relative weight. The energy and climate risks carry the highest importance rating of 0.33 in the assessment because Algeria generates power from fossil fuels while desalination plants require substantial energy consumption. The expanding domestic and export commitments on energy resources create a crucial challenge for sustaining water production systems which depend heavily on energy consumption. The concern fits Algeria's environmental goals while supporting the country's international climate agreements to decrease its carbon emissions. Within this category, 'High energy demand increasing carbon footprint' is the most pressing issue (0.41), followed by 'GHG emissions' (0.25), 'Rising operational expenditures (OPEX)' (0.19), and 'waste heat discharge' (0.15).

Social risks hold a significant position (0.261) because citizens worry about the availability of water and its affordability. The public in Algeria has expressed negative reactions about water service quality and uneven distribution patterns that affect peri-urban and rural territories. Public views about desalination will affect its general acceptance because they often focus on whether benefits are distributed fairly among different regions and sectors. The most prominent social sub-concern is 'High capital expenditures (CAPEX) for infrastructure' (0.45), followed by the 'need for substantial subsidies or tariffs to keep desalinated water affordable' (0.36), while concerns like 'fisheries loss' (0.12), 'coastal tourism decline' (0.03), and 'noise pollution' (0.03) were considered much less significant. Marine ecosystem damage follows as the third major concern (0.234), highlighting awareness of environmental consequences from brine discharge along Algeria's Mediterranean coast. 'Biodiversity loss from entrainment and brine discharge' is the leading issue in this category (0.34), followed by 'habitat destruction from salinity and chemicals' (0.22), 'seabed pollution and bioaccumulation risks' (0.21), 'seagrass loss' (0.12), and 'disruption of marine food chains' (0.11).

Its lower ranking compared to energy and social risks may reflect limited public awareness, a lack of comprehensive environmental monitoring, or the perception that marine impacts are more localized or manageable in the short term. In Algeria, the top mitigation priorities for desalination are energy use mitigation and social mitigation strategies, reflecting concerns over high energy demands and the importance of public acceptance and equitable water access. Site selection is moderately important, while brine discharge, IWRM, and intake mitigation rank lower—possibly due to institutional limitations or less immediate concern. The results highlight a focus on practical, high-impact strategies to enhance sustainability and social trust, with environmental safeguards viewed as secondary but still relevant.

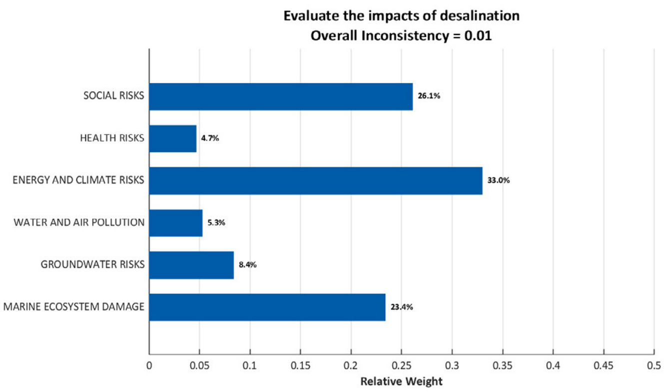



**Figure.5** *(a) Relative weights of desalination impacts in Algeria.*

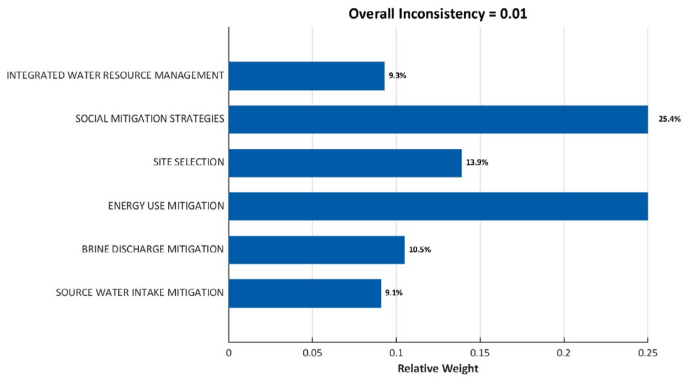



**Figure.5** *(b) Evaluation of mitigation strategies to address desalination impacts.*

## *Tunisia*

Energy and climate risks combined with social risks and marine ecosystem damage constitute around 70% of the total weight in the assessment of desalination impacts in Tunisia. Energy and climate risks stand as the primary concern at 0.39 because of Tunisia's increasing worry about maintaining sustainable water production that requires large amounts of energy. The energy sector of Tunisia faces significant pressure due to its dependence on fossil fuels and rising electricity requirements. Tunisia needs to address the critical challenge of implementing desalination into its water supply system because it requires avoiding substantial increases in carbon emissions while also dealing with the country's climate change threats and minimal renewable energy adoption. Within this category, the most concerning sub-impact is 'High energy demand increasing carbon footprint' (0.36), followed by 'GHG emissions accelerating climate change' (0.26), 'OPEX from energy-intensive operations and carbon taxes' (0.24), and 'waste heat discharge' (0.14).

The social risks component holds a weight of 0.28 because Tunisians continue to worry about equal access to water services and affordable prices and institutional trustworthiness. The public understanding of desalination in Tunisia emerges from general social and economic factors which affect water service distribution and raise questions about infrastructure management systems. Social acceptance along with fair distribution systems and transparent practices represent essential elements for obtaining public backing of upcoming desalination projects in the future. Among social concerns, the most significant sub-criteria are 'Need for substantial subsidies or tariffs to keep desalinated water affordable' (0.43) and 'High capital expenditures (CAPEX)' (0.37), while concerns such as 'Noise pollution' (0.06), 'Fisheries loss' (0.09), and 'Coastal tourism decline' (0.05) were considered less critical. The ecological vulnerability of Tunisia's Mediterranean coast becomes evident through the high score of marine ecosystem damage (0.184). The restricted water circulation makes brine discharges dangerous for marine biodiversity in affected areas.

Specifically, ‘Biodiversity loss from entrainment and brine discharge’ (0.29) and ‘Habitat destruction due to salinity and temperature’ (0.28) received the highest sub-ratings, followed by ‘Seagrass loss’ (0.18), ‘Disruption of marine food chains’ (0.14), and ‘Seabed pollution and bioaccumulation risks’ (0.11). Research participants assign lower significance to groundwater risks (0.064) along with water and air pollution (0.055) and health risks (0.027). Local and managed challenges appear to cause less concern than broader energy and social issues do. The perception of desalination as an aquifer substitute instead of an aquifer degrading factor leads people to view groundwater risks as less urgent.

In Tunisia, top desalination mitigation priorities are energy use mitigation and social mitigation strategies, reflecting concerns about high energy dependency and the need for public trust and equity in water access. Site selection is moderately important, while brine discharge, IWRM, and intake mitigation are lower priorities—likely due to limited capacity or a focus on more immediate challenges. The results emphasize the need for sustainable energy integration and socially inclusive planning in future desalination efforts.

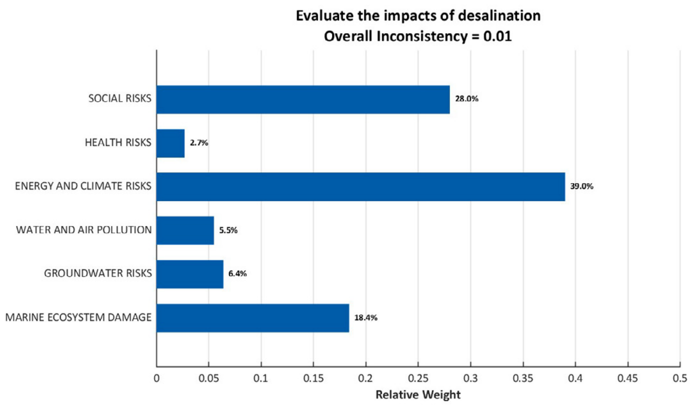



**Figure.6** *(a) Relative weights of desalination impacts in Tunisia.*

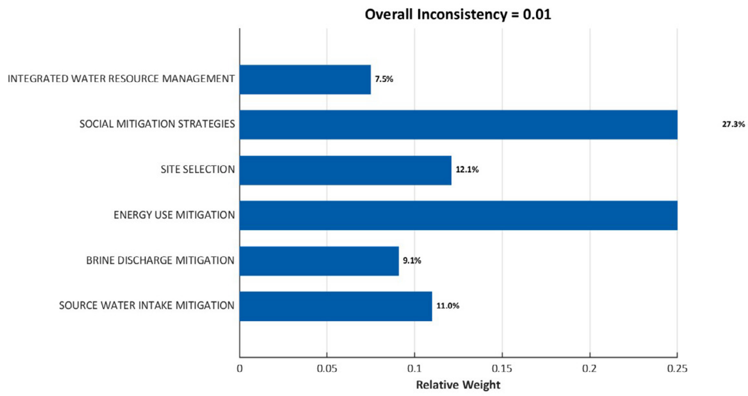



**Figure.6** *(b) Evaluation of mitigation strategies to address desalination impacts.*

## *Comparative Analysis of Country-Level Results*

The results of this study highlight both convergences and divergences concerning perceptions of desalination impacts and mitigation priorities among Spain, Greece, Israel, Libya, Algeria, and Tunisia. All six nations identify desalination as an essential approach to mitigating water scarcity. Nevertheless, prioritisation among environmental, social, and technical concerns differs considerably, influenced by varying contexts related to infrastructure quality, governance structures, energy availability, and public attitudes.

Across the majority of these countries, energy and climate-related risks represent a primary concern. This is especially evident in Greece (0.539), Israel (0.499), Libya (0.345), Algeria (0.33), and Tunisia (0.33). These countries uniformly acknowledge the high energy demand inherent in desalination technologies, alongside their consequences for national greenhouse gas emissions, energy security, and operational expenditures, particularly where there is heavy reliance on fossil fuels or in regions lacking integrated energy grids. Conversely, Spain uniquely prioritises social risks highest (0.43), reflecting heightened concerns around issues such as equity, affordability, and public acceptance. Spain’s mature regulatory frameworks underscore the central role that societal perceptions of fairness play in the successful implementation of desalination projects.

Social concerns are similarly significant in Libya (0.25), Algeria (0.261), and Tunisia (0.261), where issues such as affordability, governance transparency, and equitable rural access stand out. These nations encounter structural difficulties such as fragmented institutional arrangements and pricing models heavily reliant on subsidies, which amplify public sensitivities. In contrast, Israel (0.052) and Greece (0.111) demonstrate lower levels of concern for social risks, likely due to their more robust institutional frameworks and broader societal support for desalination initiatives.
Concerns regarding impacts on marine ecosystems are notably prominent in Tunisia (0.234), Algeria (0.234), and Israel (0.287), primarily due to brine discharge affecting coastal areas with limited water circulation or dense desalination plant distributions. Spain (0.129) and Greece (0.047), however, appear more confident in their existing mitigation measures or perceive these environmental impacts as less severe. Overall, risks related to groundwater, human health, and air and water pollution are considered

relatively less critical across all six countries. For instance, low levels of concern are reported in these categories by Israel, Spain, and Tunisia, often attributed to existing treatment protocols or the perception that these risks are manageable or effectively regulated.

Despite these contextual differences, three mitigation strategies consistently emerge as highly prioritised. Energy-use reduction is universally emphasised, particularly by Greece (0.222), Israel (0.208), Libya, and Tunisia, highlighting a collective urgency for the adoption of renewable and low-carbon energy solutions. Social mitigation strategies receive considerable attention in Spain, Algeria, Libya, and Tunisia, driven by public discourse focused on affordability and equity. Additionally, strategic site selection ranks highly in Spain (0.212), Greece (0.216), Israel (0.209), and Libya, underscoring the necessity of considering ecological sensitivity and potential land-use conflicts. Conversely, mitigation strategies addressing brine discharge, source water intake, and Integrated Water Resource Management (IWRM) generally receive lower priority, particularly in nations with limited technical capabilities or where environmental planning frameworks are still evolving (e.g., Libya, Tunisia, Algeria).

Collectively, these findings underscore the necessity of aligning desalination policies with the unique challenges and capacities of individual countries. For example, Spain and Israel, benefiting from robust institutional frameworks and extensive desalination experience, focus predominantly on optimising and integrating existing systems. Conversely, Tunisia, Libya, and Algeria grapple with more foundational challenges surrounding affordability, governance, and energy security, directly influencing their perceived risks and strategic priorities. Ultimately, this comparative analysis underscores that, although desalination is broadly recognised as an effective response to Mediterranean water scarcity, its practical implementation varies significantly across national contexts. Future regional collaboration and knowledge exchange—especially regarding social governance, environmental safeguards, and energy integration—could provide critical avenues for advancing more sustainable and socially acceptable desalination practices throughout the region.

## CONCLUSION

This study offers a comparative assessment of desalination impacts and corresponding mitigation priorities across six Mediterranean countries—Spain, Greece, Israel, Libya, Algeria, and Tunisia—based on the insights of 20 national experts. The results reveal that while desalination is broadly recognized as a critical solution for addressing water scarcity in the region, its long-term sustainability depends on how well associated environmental and social challenges are understood and managed.

Energy and climate risks consistently emerged as one of the top concerns, particularly in countries with energy-constrained or fossil fuel-dependent systems such as Libya, Tunisia, and Algeria. In contrast, social risks were especially prominent in Spain and Tunisia, reflecting sensitivities around public acceptance, equity, and governance. Environmental concerns, such as marine ecosystem damage, also featured prominently in countries with extensive coastal desalination infrastructure.

When it comes to mitigation strategies, energy use mitigation was universally prioritized, reinforcing the urgent need for cleaner, more efficient desalination technologies. Site selection and social mitigation strategies also ranked highly, emphasizing the importance of planning and public engagement in ensuring project success. Meanwhile, strategies like brine discharge and source water intake mitigation, though important, tended to receive lower priority, possibly due to perceived manageability or regulatory confidence.

Overall, the findings suggest that there is no one-size-fits-all solution. Instead, each country's strategy must be shaped by its unique combination of technical capacity, environmental context, and social dynamics. Moving forward, greater regional collaboration, investment in sustainable technologies, and stronger institutional frameworks will be essential to maximize the benefits of desalination while minimizing its risks across the Mediterranean.

# STRENGTHENING THE SUSTAINABILITY AND RESILIENCE OF THE DESALINATION SECTOR IN THE MEDITERRANEAN

AUTHOR : FIRAS MARSIT

Water reservoirs and reverse osmosis equipment in a desalination plant © tifonimages


## Abstract

This paper explores existing legal regimes governing seawater desalination, particularly brine discharge management in Mediterranean countries, with a focus on Southern States. It aims to identify solutions to foster a sustainable seawater desalination considering external constraints (climate change, demographic growth) and green hydrogen development in Mediterranean countries.  Sustainable or viable seawater desalination consists of reducing marine pollution through valorization of minerals contained in brine, preventing social water-use conflicts, promoting low-carbon emission of desalination activities and ensuring the sector's financial viability. Regionally, desalination governance mainly involves the United Nations Convention on the Law of the Sea (UNCLOS), the Barcelona Convention and its Land-Based Sources (LBS) Protocol, and United Nations Environment Program (UNEP) guidelines applied to desalination activities. Evolution of these international environmental frameworks depends on technological, economic, and social factors such as critical water needs, pollution control costs, institutional capacity, and scientific understanding of ecological impacts. During the period when UNCLOS and the Barcelona Convention were drafted; desalination's environmental impacts were less documented. With its growth, particularly in the context of energy transitions and brine treatments advancement, revisiting existing frameworks and potentially updating the Barcelona Convention could be essential. This report outlines legal, technical, economical, and socio-environmental aspects of seawater desalination, green hydrogen development based on desalination, and renewable energy powering desalination plants, while distinguishing innovative brine valorization techniques to propose a sustainable desalination in the region.

## INTRODUCTION

The Mediterranean basin is a climate change hotspot, experiencing an alarming depletion of groundwater resources, intensified by rising temperatures and declining rainfall. To manage this escalating water scarcity, many countries are increasingly turning to seawater desalination for domestic potable water and irrigation needs. Nevertheless, seawater desalination processes are energy-intensive, ecologically impactful due to brine discharge, and economically debatable. Additionally, the ambition to develop green hydrogen in several Mediterranean States requires substantial volumes of freshwater, further increasing water demand. In this sense, it is essential to adopt more sustainable desalination technologies that rely on renewable energy and that have lesser environmental impact, while structuring an adapted and efficient regional governance. This approach could contribute to balancing energy transition, resilient water management, and the conservation of marine biodiversity in coherence with the Sustainable Development Goals (SDGs). Thus, a central question guides the research: is the governance framework regulating desalination and its environmental externalities in the Mediterranean—particularly the regional instrument—fit for purpose in light of fast-moving technological, energy, scientific, socio-economic, and environmental dynamics? In other words, can it enable a genuinely sustainable model of seawater desalination that cuts greenhouse-gas emissions, minimizes brine discharges and marine ecological harm, and meets essential social needs? To answer this, the paper is structured around 3 topics: (1) Legal regimes of Western and Central Mediterranean countries (Italy, Tunisia, Algeria, Spain, Morocco, Greece, and Egypt) are assessed to provide an overview of the governance of desalination and to highlight key national laws framing EIA and brine effluents; furthermore, a critical review of supranational frameworks (UNCLOS, Barcelona Convention, UNEP guidelines) outlines their strengths and limitations proposing enhanced regional cooperation, harmonized environmental assessments, and legal/policy recommendations; (2) techno-economic solutions for reducing desalination impacts, including ''brine mining'' innovations, are identified and evaluated for operational and economic feasibility as well as the economic feasibility of coupling desalination with renewable energy sources; (3) finally, an essential component analyzes links between desalination and green hydrogen production, addressing water and energy demands for electrolysis and socio-environmental constraints. The article covers key dimensions of sustainable seawater desalination such as energy efficiency optimization, water recovery of desalination process enhancement, minimization of ecological impacts, as well as reinforcement of social acceptability and sector financial viability. By identifying legal gaps and solutions from a regional viewpoint, the intent is to develop reflection on the possibility to esquisse or renew the current regional governance that would foster a sustainable seawater desalination reflecting new technical innovations as well as evolving environmental, and socio-economic dynamics.

## DATA COLLECTION METHODOLOGY

The research is based on empirical data analysis and case studies. A literature review and key data focusing notably on Southern Mediterranean countries provide a comprehensive overview of seawater desalination development stage. The study highlights the disparities between each Mediterranean country on how brine effluents from desalination plants are framed and stresses divergences between key aspects of the national legislation. The purpose is to lead a comparative study on the legal governance of desalination and its associated environmental impact, to examine potential impediments in implementing the Barcelona convention and UNEP guidelines at a national scale as well as to determine the legal gaps of the Barcelona convention itself. Qualitative analysis draws on governmental documents presenting legal frameworks administrating desalination in mostly western Mediterranean countries. A study case related to Tunisia is retained for the research notably in the section pinpointing the environmental impact of Seawater desalination. This choice is justified by the fact that the study aims to focus on the countries of the southern shore and Tunisia is the among the few States that has available official governmental documents presenting environmental impact assessments (EIA) of seawater desalination.

In this paper, EIA and technical documents (scientific publications) describe the social implications of desalination, ecological impacts from brine discharge, and technical-economic feasibility of mitigation measures such as the development of Minimum Liquid Discharge (MLD) and Zero Liquid Discharge (ZLD) techniques. This combined methodology enables a multidimensional approach covering technical (environmental impacts, energy efficiency, techno-economic feasibility) and socio-environmental factors (acceptability, governance), aiming for a systemic and contextualized analysis.

For the section dealing with MLD and ZLD feasibility in the Mediterranean, the analysis is based on a limited number of studies. The intention was not to compile all available references on MLD/ZLD worldwide, but to retain the most relevant and comprehensive sources for the Mediterranean context. The main study used is recent and specifically focused on the Eastern Mediterranean. It combines technical, economic, and environmental aspects in a way that few other publications do. It also goes beyond general feasibility by detailing how brine could be recovered and valorized in the market—an essential consideration when assessing circular economy potential. This makes it particularly strategic from the regional perspective. The focus is placed on the Forward osmosis (FO) and Reverse osmosis (RO) hybrid approach. Furthermore, the case of green hydrogen development associated with seawater desalination is apprehended. A study case of Tunisia has been chosen as a national strategy on green hydrogen development has been recently adopted by the Tunisian government which clearly states that seawater desalination will be developed to produce hydrogen. Tunisia represents a good example to illustrate the broad implications of a sustainable seawater desalination which could be achieved thanks to green hydrogen. In fact, few countries have developed commercial desalination based on MLD-ZLD due to intensive energy requirements. That issue is nevertheless solvable as green hydrogen can boost renewable energy production. It will be demonstrated in this paper that energy, elimination of brine discharge and green hydrogen are linked as a ''triangular'' scheme.

## RESULTS - PRESENTATION OF THE KEY FINDINGS

### *Roles and Limitations of Supranational Legal Frameworks in Addressing the Social and Environmental Challenges of Desalination*

#### *a) Role of the Law of the Sea in Regulating Brine Discharges into the Mediterranean Marine Environment:*

**Main Objectives of Part XII of UNCLOS and its Provisions Applicable to Seawater Desalination:**

Part XII of the UNCLOS is the international instrument governing the environmental impacts of human activities on the marine environment, notably those generated by desalination plants. It imposes an obligation on States to take measures to prevent, control, and reduce marine pollution, particularly from land-based sources. Under the Law of the Sea, States are required to adopt the following approach to eliminate or mitigate all sources of marine pollution:

1. Prevention, which may infer to:
- Select appropriate sites, avoiding environmentally sensitive areas and adopt innovative technologies to reduce polluting such as the concentration of brine discharged;
- Favor non-polluting alternatives and actively prevent the introduction of harmful substances into the sea.

2. Impact Reduction, that may imply to:
- Dilute brine discharges in a controlled manner to protect marine biodiversity and apply strict discharge quality standards defined by the competent authorities.
- Use advanced multi-orifice diffusion systems to better distribute brine and avoid salinity spikes and choose ecosystem-friendly seawater intake systems;

3. Control (in the event of an accident or proven pollution):
- Implement procedures to contain and neutralize pollutants;
- Carry out environmental restoration actions to limit long-term impacts.

The key articles of Part XII include:

- Article 194: Obligation to adopt all necessary measures to prevent, reduce, and control pollution from all sources, including that from land-based installations (such as desalination plants).
- Article 204: General obligation for States to conduct marine environmental impact assessment
- Article 207: Obligation to adopt national legislation and regulation to diminish land-based sources of pollution.

Limitation of Part XII of UNCLOS:

The requirements set out in UNCLOS constitute State obligations of diligence which are procedural obligations not obligations of results. Moreover, the environmental provisions of Part XII are mostly general in scope and remain subject to interpretation and are dependent on regional and sectoral treaties to clarify their scope, increase the effectiveness of the regulation of the activities concerned, and minimize their impact on the marine environment through appropriate technical standards. However, sectoral or regional instruments are relatively incomplete in regulating the desalination sector in the Mediterranean. As to date, no legally binding international agreement relating to desalination activities has been adopted, and even the Barcelona Convention and its protocols are more general than specific to frame effectively seawater desalination. Furthermore, it should be noted that UNCLOS considers the level of development and capacity of developing countries to implement Part XII of UNCLOS. The Law of the Sea, through Part XIV, advocates for capacity-building initiatives to support countries from the Global South.

Part XIV-Technology Transfer:

Part XIV of UNCLOS promotes the transfer of marine technology to support States, in particular developing countries. This includes scientific and technical cooperation. Certain provisions specifically call for the development of regional organizations and technical standards to regulate desalination activities. By encouraging scientific cooperation and the transfer of marine technology, Part XIV effectively complements the prevention, control, and reduction obligations set out in Part XII. Despite their general nature, these two parts are essential for regulating the environmental impacts of desalination plants coherently and effectively.

### *b) Role of the Barcelona Convention*

The Barcelona Convention and its LBS Protocol play a key role in regulating brine discharges in the Mediterranean by imposing regulatory requirements on discharges from land-based sources into the marine environment, including those resulting from seawater desalination. Although desalination is not explicitly designated as a priority, the principles of the protocol apply, particularly those relating to polluting substances, environmental impact assessment (EIA), and best available technologies. In addition, the Ecosystem Approach adopted by UNEP/MAP aims to ensure Good Environmental Status (GES) in the Mediterranean by integrating brine discharge management with ecological objectives, such as preserving biodiversity, preventing eutrophication, and limiting hydrographic alterations. Through successive decisions, notably IG.17/6 and IG.21/3, the implementation of GES is based on monitoring indicators and targets, thus strengthening the regulatory and monitoring framework for the impacts of desalination. The integration of these elements into the licensing and discharge monitoring processes ensures that desalination activities are sustainable and attenuate their impact on Mediterranean marine and coastal ecosystems.

### *c) Role of UNEP and its Guidelines*

The Guidelines on the Management of Desalination Activities, developed by UNEP, play a pivotal role in EIA and impact monitoring of desalination facilities in the Mediterranean Sea. They aim to ensure optimal management of environmental effects. EIAs are expected to address several fundamental aspects, including:

- Project Objective and Need: The EIA must clearly present the desalination project, including its location, its connections to other industries and infrastructure, and the water needs of local communities or industries. This helps justify the project's existence and demonstrates that it meets a regional or local need.
- Technology and Discharge Techniques: A detailed description of the desalination technologies used (RO or other), their capacity, energy consumption, and discharge characteristics is essential for assessing their environmental impacts. Discharges, including their volume, toxicity, and effect on the marine ecosystem, must be considered to minimize risks.
- Brine Dispersion Modeling: Modeling brine discharges is essential for predicting their dispersion in the marine environment and their effect on water quality, biodiversity, and protected species. This stage simulates the short- and long-term effects of projects.
- Mitigation measures: Best environmental practices and best available technologies must be incorporated into the EIA to minimize impacts. This includes the use of more energy-efficient technologies, chemical management, and methods to reduce brine concentration and increase discharge dilution. During the construction phase, environmentally friendly techniques, such as waste recycling and habitat restoration, must be implemented.
- Monitoring and follow-up: Rigorous monitoring of environmental impacts throughout the facility's lifecycle is imperative. The monitoring plan must be based on the EIA and adjusted based on the results obtained. This includes biannual measurement campaigns of water quality, sediments, and marine biota, including physicochemical and biological parameters. The results must be published regularly to adjust mitigation measures as needed.

Thus, the guidelines on desalination management, incorporating monitoring measures and cutting-edge technologies, aim to ensure that projects are not only technically viable, but also environmentally and socially responsible, facilitating the sustainable management of marine resources.

### *d) Limitations of the Barcelona Convention*

Although the Barcelona Convention and its LBS protocol on land-based sources (LBS) establish a regional framework to regulate brine discharges from desalination, these frameworks have several limitations that prevent comprehensive consideration of desalination issues in the context of energy transition and sustainable resource management. Their main limitations are the following:

- Inadequate integration of advanced discharge management technologies: The Guidelines and the LBS Protocol focus on the management and dilution of brine discharges and promote the use of best technologies, but don't incorporate a feasibility assessment of Zero Liquid Discharge (ZLD), Minimal Liquid Discharge (MLD). Brine mining could reduce the impacts of saline discharges by recovering valuable minerals and minimizing pollution of coastal and marine ecosystems. Moreover, developing a techno-economic feasibility study template to assess the possibility to combine MLD and ZLD with an active desalination plant would be highly relevant.
- Lack of a multi-use approach: Although the guidelines address the environmental and social impacts of desalination, they do not adequately consider a multisectoral approach that promotes synergies of water use. For example, the feasibility of using desalinated water for different purposes such as irrigation and more are not sufficiently studied in current impact studies, even though such an approach could strengthen the resilience of territories to climate change and meet basic social needs, particularly in countries on the southern shore.
- Gaps in renewable energy feasibility assessment: The current framework does not provide a detailed methodology for assessing the energy consumption of desalination plants operating in ZLD or MLD or their compatibility with renewable energies. This analysis is crucial for determining the economic viability of a project and reducing greenhouse gas emissions.
- Lack of monitoring and dynamic adaptation: While environmental monitoring of brine discharges is planned, it remains limited in duration and frequency, which can lead to an underestimation of long-term impacts. Furthermore, there is a lack of a dynamic adjustment framework based on new scientific and technological advances to improve the environmental performance of desalination plants.
- Need for transboundary pollution assessment and cumulative impact assessment: Seawater desalination activities are very concentrated in the Mediterranean zone and would likely continue to increase. The UNEP and its guidelines advocate for transboundary impact assessment. Nevertheless, such studies are lacking in scientific literature and reports made by competent international institutions. Likewise, it is fundamental that guidelines are updated to enable the mandatory proceeding of cumulative environmental impact assessment underpinned by seawater desalination and other maritime activities.

Water treatment plant at sunset © tuachanwatthana

## *Overview of the development status of the desalination sector in Mediterranean countries and the national legal framework administrating the sector*

### *a) Tunisia*

**Sector context**

Tunisia has limited and unevenly distributed water resources across the country. Drought caused by climate change and population growth are major factors exacerbating water stress. In 2014, water availability per capita per year was 440 m³, while the minimum considered by the UN is 1000 m³. The Water Sector Strategy for 2050 was designed by the national seawater desalination agency to moderate geographic disparities and mitigate the imbalance between water supply and demand. The strategy envisages desalinating 265 million m³ by 2050. The implementation of programs to develop the desalination sector, under the strategic framework, is led by the Ministry of Agriculture and the Tunisian National Water Development and Distribution Company (SONEDE). Currently, three seawater desalination plants are in operation (one in Djerba, which was commissioned in 2018, as well as the Sfax and Zarat plants, which were inaugurated in 2024). Three additional plants will be built in 2025 (Sousse, Zarzis, and Mahdia plants).

**Legal framework**

In Tunisia, seawater desalination activities are governed by a solid legal framework aimed at limiting their environmental impact. The National Seawater Desalination Agency, created by a Decree, has the role of managing plant construction and launching strategic policies to develop the sector.  The Water code amended by Law No. 2001-116 of November 26, 2001, asserts that the desalination of brackish, salty, and seawater must be carried out using technologies that reduce pollution from production residues and mineral concentrations. This legislation also encourages the development of a national sustainable water management policy, including the rationalization of consumption, the development of water resources, and the integration of treated wastewater into the agricultural and non-agricultural. Furthermore, Decree No. 2005-1991 requires desalination units to carry out an environmental impact study (figured in Annex I of the Decree). Regarding brine discharges, the Water Code (Law No. 75-16 enacted on March 31, 1975) and its amendments prohibit any discharge, including brine, into groundwater or other zones having an ecological and economic importance. The objective is to conserve freshwater resources, ensure public health, preserve sensitive marine areas and protect vital economic sectors such as coastal tourism . This regulatory framework aims to ensure a balance between the development of desalination and the preservation of aquatic ecosystems in Tunisia. Also, Article 6 of Decree No. 2005-1991 on environmental impact studies imposes the obligation to reduce or eliminate the harmful effects of an activity, or to compensate for damage caused to the environment by industries. Decree No.2002-335 impose to assess Ph, temperature, chemical concentration and salinity variation induced by brine effluents. Thus Tunisian legal framework encourages the adoption of solutions aimed at limiting the environmental impacts of desalination, particularly by encouraging the reduction or elimination of brine discharges. This approach creates an environment conducive to the development of advanced technologies, such as MLD and ZLD.

### *b) Algeria*

**Sector context**

Algeria ranks second in the Mediterranean region in terms of freshwater production seawater desalination plants with medium to high capacity, between 20,000 and 125,000 m3 /day. The country accounts for 20% of the region's total RO desalination capacity, behind Spain. To address water stress, meet industrial needs, and cope with demographic pressure, Algeria has focused on desalination for nearly twenty years, particularly in the cities of the north of the country. With a vast coastline of 1,200 km, the country has 21 desalination plants (2024 data) in operation and seven more under construction, providing 17% of the water consumed and supplying 6 million people. Mactaa desalination plant, located in the Wilaya of Oran in the is among the biggest RO station worldwide with a capacity of 500,000 m3 /day.

**Legal framework**

In Algeria, the legal framework governing seawater desalination activities is based primarily on a series of executive decrees and sector-specific laws that frame permits grants, ensure environmental protection, and regulate brine discharges.

The construction of desalination plants is authorized by executive decrees. The management and development of technical standards are handled by the Ministry of Water Resources, notably through the Desalination Directorate, as specified in Executive Decree

No. 16-88 of March 1, 2016. Desalination activities require a water resource use concession, in accordance with Executive Decree No. 11-220 of June 12, 2011, which triggers an environmental impact assessment as a prerequisite (Article 7). More broadly, the framework for impact assessments in Algeria is governed by Executive Decree No. 07-145 of May 19, 2007 and its amendments, which define the approval procedures for environmental impact assessments and notices applicable to designated projects. Although, it is not clear whether desalination plants are within the scope of this regulation or not. Furthermore, coastal and environmental protection is ensured by Law No. 03-10 relating to environmental protection within the framework of sustainable development, which imposes prevention and control measures from all pollution sources altering marine habitats. These laws aim to limit the ecological impact of seawater desalination by regulating brine discharges. In addition, Algerian standards confine chemical and brine concentration released into the sea. The national standards set notably a limit of 35500 mg/L for the salinity, 10 mg/L for the discharge water display and 120 mg/L for the hydrocarbons.

### *c) Morocco*

**Sector context**

Seawater desalination in Morocco is part of a strategic vision aimed at addressing the growing challenges associated with the scarcity of water resources, exacerbated by the effects of exceptional drought and a particularly worrying water deficit in certain regions. In this context, the government launched the National Program for Drinking Water Supply and Irrigation 2020-2027, which prioritizes the development of desalination as a sustainable solution to secure access to water resources and support domestic, agriculture and industrial uses. It is worth noting that most of the desalination units are alongside the Atlantic shore.

**Legal framework**

Seawater desalination is framed by several laws to foster its sustainable and environmentally friendly development. Water Law No. 36-15 frames desalination activities and ''establishes the rules for integrated, decentralized, and participatory management of water resources'' (translated quote). It mandates environmental impact studies to be conducted before any project susceptible to harm to the hydric public domain, in order to assess the effects on ecosystems, and socio-economic uses. Law No. 12-03 on Environmental Impact Studies reinforces this requirement by mandating post-commissioning monitoring to ensure the effectiveness of mitigation measures. This framework seems to pertain indirectly to the desalination sector. Indeed, the annex of the former law doesn't specify that desalination units are subject to EIA, but any evacuation activities on marine ecosystem must be assessed and consequently may comprehend seawater desalination industries. Furthermore, Law No. 81-12 on the Coastline advocates for the integrated management of coastal zones, and aims to prevent coastal and marine habitats degradation, including due to brine discharges, and ensure its rehabilitation.  Decree No. 2-04-553 of 2005 and a joint ministerial order passed in 2013 set general limit values for discharges into surface or groundwater and regulate all industrial discharges likely to alter the physical, including thermal and radioactive, chemical, biological, or bacteriological, characteristics of surface or groundwater. However, these frameworks do not specify whether surface water includes seawater or not. Otherwise, Dahir No. 1-12-25 (August 2, 2012) promulgating Law No. 23-12 amending Law No. 28-00, calls for the recovery of industrial waste and could then serve as a legal basis for promoting ZLD-MLD. To summarize, Moroccan regulations aspire to develop seawater desalination from a sustainable development angle, reconciling water security with the preservation of marine and coastal ecosystems.

### *d) Italy*

**Sector context**

In Italy, there are 216 RO desalination plants operating in Italy based on the DesalData Database. According to the IDRA (International Desalination and Reuse Association World Congress), they are mainly plants operating with low capacity (less than 10,000 m3 per day), except for the Sarroch plant in Sardinia and Calabria, which have a capacity of 12,000 m3 and 18,000 m3 per day, respectively. Desalination plants are planned in Puglia and Sicily with a capacity exceeding 50,000 m3 per day.

**Legal framework**

Italian legislation has gradually evolved to regulate brine discharge from desalination plants in response to climate change and dwindling water resources. The main legal frameworks are:

- Law 152/2006:

This law primarily regulates the discharge of industrial and municipal wastewater into the sea and sets a Total Suspended Solids limit of 80 mg/L near discharge point.

It addresses pollution generated by brine disposal by setting a salinity limit to protect mollusk life, stipulating that the increase in salinity near a discharge point must not exceed 10% of the natural salinity of seawater. However, it does not clearly define the extent of the mixing zone.

- Law 60/2022:

This is the first Italian law requiring an Environmental Impact Assessment (EIA) for desalination plants. All facilities must obtain authorization through an EIA for their construction and discharge operations.

- Law 39/2023:

In a context of increasing water scarcity, this law limits the EIA requirement to desalination plants with a production capacity greater than 17 280 m³ per day. It introduces a stricter limit on brine discharge compared to the 2006 law and defines the Italian regulatory mixing zone:

Within 50 meters of the discharge point, the increase in salinity must not exceed 5% of the natural salinity of seawater.

Effluent discharge is strictly permitted only at sea and prohibited in freshwater. Other chemical parameters remain in compliance with Law 152/2006, except for sulfates and chlorides present in brines, which are regulated separately.

In summary, Italy frames brine discharge through laws on industrial wastewater (152/2006) and environmental impact assessments legislation (60/2022, 39/2023). Regarding salinity limits, discharged brine must not increase salinity by more than 10% near the discharge point, and at 50 meters, the increase must not exceed 5%. Large facilities are required to conduct an EIA, while smaller (less than 17 280 m³/jour) ones are exempt. Brine discharge is only permitted at sea and is prohibited in groundwater or fresh surface water.

## *e) Egypt*

**Sector context**

The Egyptian water desalination program, adopted as part of the implementation of the National Water Strategic Framework, aims to increase total desalination capacity from 3.35 million m³ (Mm³) per day (2024) to 8.85 Mm³ per day by 2050. This program seeks to attract strategic foreign and local investors to finance, build, and operate this infrastructure while using renewable energy. This program is complemented by other initiatives aimed at decarbonizing the desalination sector. Indeed, thanks to the program entitled «Water Desalination using Renewable Energy,» five desalination plants powered by renewable energy, financed by public-private partnerships, are planned in the coming years. On the Mediterranean coast, the establishment of three desalination plants is planned in the cities of Port Said, Ras El Hekma, and Alexandria, with respective capacities of 100,000, 50,000, and 125,000 m3 per day.

**Legal framework**

The legal framework for the sector is based on Law No. 147 of 2021 on Water Resources and Irrigation, which governs water management and desalination, as well as Law No. 4 of 1994 on the Environment, amended by Law No. 9 of 2009, which regulates the management of waste and industrial discharges in order to limit the environmental impact of desalination projects. This law, supplemented by Decree No. 338 of 1995, requires an environmental impact assessment (EIA) before issuing any permit for a new project or the expansion of an existing facility. The EIA must assess water sources and uses, discharges from desalination plants, and options for reuse and treatment of brine prior to discharge. In addition, the legislation prohibits any discharge into the marine environment, including brine, within 500 meters of the coastline. The discharge of brine into fishing areas, bathing areas, and nature reserves is prohibited in order to preserve the economic, ecological, and esthetic value of the sites.

## *f) Greece*

**Sector context**

Greece is among the Mediterranean countries counting the most of operating seawater desalination plants behind Spain and Italy. Indeed, ''more than 160 desalination plants operate in Greece with a total production of more than 150,000 m3/day. In terms of supply water, 56% is seawater, while 41% is brackish water. As far as the use of the produced desalinated water in Greece is concerned, 48% is the supply of municipalities, 31% covers industrial needs, 16% covers tourist requirements, with the remaining 5% covers the needs of energy production plants and the needs of the Greek military. Reverse osmosis is the most popular desalination process in Greece, as 75% of the desalinated water is produced by reverse osmosis desalination units. Desalination units on the islands are of small capacity ranging from a few hundred cubic meters per day to a few thousand cubic meters per day. The largest part of the desalination systems is operating on islands serviced by isolated electricity grids. These grids in most cases are powered by diesel/oil generators. The rest are installed in interconnected islands. The interconnection is realized using submerged cables.''

**Legal framework**

In Greece, seawater desalination is regulated by national laws, Ministerial Decree (MD) Joint Ministerial decrees (JMD) designed to manage water use and control environmental impacts. With regards to environmental protection, brine discharge, and EIA, the Law 1650/1986 sets out the principles for protecting the environment, complemented by Law 3010/2002, Law 4014/2011 and JMD 5688/2018, which defines the permitting procedures and classifies projects according to their environmental impact. Moreover, JMD 18186/271/1988 and its amendments set limit Values and restrictions with regards to dangerous substances contained in wastewater. JMD 15393/2332/2002 (L1022), JMD 13727/5.8.2003 (L1087), MD 145799 (L1002)/2005 and their amendments categorize public and private projects and activities in view of their environmental impacts. Facilities producing 100 m³/day or more are considered high-risk and must undergo a strict EIA process; those producing less than 100 m³/day follow a lighter regime with general protection standards, and facilities producing 10 m³/day or less for municipal use may be exempt if they meet technical and environmental requirements. Public-interest projects benefit from simplified procedures. JMD 69269/5387/1990, JMD 75308/5512/1990 and their amendments set the requirements for EIA content and ensure public access to information. Brine discharge requires a specific permit (MD 221/65), issued after an assessment of potential impacts on marine ecosystems. Laws 2742/1999 and 3044/2002 require the preservation of protected areas and fragile ecosystems within water management plans. Law 3199/2003, which transposes the EU Water Framework Directive (2000/60/EC), introduces river basin management and, combined with MD 43504/2005, allows for permits to use seawater with a validity of up to ten years. The construction and operation of desalination plants require a site permit (with exemptions for small units), an operating permit reviewed every five years, a brine discharge permit (MD 221/65 and its amendments), as well as comply with potable water standards (JMD Y2/2600/01, JMD 38295/2007) and port or coastal use authorizations (Law 2971/2001).

## *g) Spain*

**Sector context**

Spain is the European leader in seawater desalination, with around 770 plants in operation. The majority of these are large-scale facilities with a capacity exceeding 10,000 m³/day. The largest is located in Torrevieja, producing about 240,000 m³/day, followed closely by the Águilas plant at around 210,000 m³/day. Most plants use reverse osmosis technology.

**Legal framework**

The country's desalination activities are governed by a well-structured legal regime aligned with European directives. Real Decreto Legislativo 1/2001- Ley del Aguas classifies desalinated water as a public resource and places desalination facilities under an authorization regime managed by the Watershed Basin Authorities (Confederaciones Hidrográficas). These authorities systematically require an EIA for any significant desalination project. This obligation is reinforced by Ley Nº 21/2013 - Ley de Evaluación Ambiental amended by Ley Nº 9/2018, which transposes EU directives (Directive 2011/92 as amended by Directive 2014/52/EU) and makes an EIA mandatory for projects with a capacity greater than 3,000 m³/day. Additionally, Ley 10/2001, de 5 de Julio, del Plan Hidrológico Nacional calls for integrated water resources management, including desalination plants, and defines desalinated water as an alternative resource to be included in Watershed basin management plans. Ley de Costas (1988) and its amendments require permits to allow brine dumping into the sea and set cap values of chemicals and other contaminants to preserve marine biodiversity.

One major regulatory gap is that Spanish law does not set explicit national limits on brine salinity or chemical composition. However, project authorizations and Environmental Monitoring Plans (EMPs) clearly include mitigation measures. These EIA and EMP requirements could serve as a legal basis to foster the adoption of MLD and ZLD practices in Spain. Moreover, the 2023 Plan Bleu report "Des mesures pour atténuer les risques et impacts environnementaux" indicated that Spanish environmental authorities set a critical salinity threshold of 38.5 PSU in EIAs to protect Posidonia oceanica seagrass meadows. For brine dispersion, salinity near the diffusers must not exceed 1 g/L within a mixing zone limited to 400 m or more. To meet these standards, multi-port diffusers are recommended as a standard measure, sometimes combined with seawater bypassing or co-location with other facilities (such as power plants or wastewater treatment plants) to ensure rapid and effective dilution. The report also underscored that «comprehensive monitoring programs should be implemented to assess the distribution of the brine plume over time and to detect any predicted salinity anomalies. These programs should cover different parameters, including physical factors (temperature, salinity, turbidity, pH, conductivity, TSS) and chemical factors (minerals, metals, oxygen, carbon, nitrogen, fluorides, chlorides, nitrates, sulfates, organic matter, hydrocarbons), as well as microbiological analyses.» (translated quote)

### *h) Libya*

**Sector context**

In 2018, Libya had about 21 desalination plants in operation, with a combined production capacity of roughly 525,680 m³ per day, and until 2002, desalination accounted for around 1.4% of the country's local water supply.  Libya has relied on thermal desalination since the 1960s and 1970s and almost 95% of the existing facilities use thermal processes, mainly multi-stage flash (MSF), while only about 5% operate with RO technology. However, the desalination sector is facing several issues. Since the Arab Spring revolution of 2011, some units are unfunctional due to limited maintenance. Besides that, according to some impact assessment studies, environmental regulations need to be updated to frame effectively brine disposal and to protect marine and coastal areas.

Major national legal gaps and challenging Implementation of LBS protocol at local scales:

The practical implementation of the regional framework in Mediterranean countries is positive but raises some challenges. Indeed, the supranational instruments primarily define general principles and obligations, leaving States responsible for translating them into precise technical regulations at the local level. However, in countries such as Tunisia, Algeria, Egypt, Greece, Spain, and Italy, the obligations to use specific techniques to mitigate the effects of brine discharges, such as the mandatory installation of multi-port diffusers to optimize brine dispersion in the marine environment, are not clearly specified in national legislation. Rather, these countries' legislative texts contain provisions, subject to interpretation, that directly or indirectly call for the use of the best techniques to reduce environmental impact. Although, even if the national framework doesn't clearly request using, for example, multi-port diffusers, they are employed in practice by all referenced countries. Similarly, even though these countries have developed rigorous legal frameworks, the effectiveness of their implementation fluctuates considerably due to uneven institutional and technical capacities, as well as sometimes insufficient levels of enforcement and monitoring. Moreover, UNEP guidelines, although followed in principle by all these States, are generally not legally binding; they are limited to guiding environmental assessments without always guaranteeing the rigorous application of the best available technologies or the strict implementation of regular monitoring measures. Thus, from my point of view, the main challenge lies in the gap between regional ambitions and local realities, with a growing need for technology transfer, harmonization of specific technical standards, and improvement of regional-national monitoring and effective control systems. Despite those gaps, countries from both South and North shore are in general using the best techniques to reduce environmental impacts but monitoring data are still lacking to draw a clear picture on the effectiveness of regulatory measures to meet marine environmental quality standards.

### ***Overview of the environmental impacts of seawater desalination in Tunisia***

**Djerba Desalination Plant**

An EIA has been published by the Tunisian government regarding the Djerba seawater desalination plant. Commissioned in 2018, this facility has a daily production capacity of 50,000 m³ (expandable to 75,000 m³). It uses a 4,900-meter(m) pipeline (2,300 meters onshore and 2,600 meters offshore) with a width of 1,500 mm to minimize environmental impact. The brine discharge pipeline includes 21 diffusers spread across 100m to enhance dispersion and mitigate the impact on benthic fauna and flora. The assessment specifically considers the impact on Posidonia seagrass meadows and outlines mitigation measures. The goal is to ensure the brine discharge does not exceed a salinity threshold of 45000mg/L, protecting these seagrasses which cannot tolerate higher salinity levels. The EIA evaluates salinity levels at distances of 100m and 200m from the discharge point, determining how far the 45000mg/L threshold extends and the affected areas. The daily brine discharge volume into the marine environment is approximately 61,112 m³. Although the Tunisian standard NT. 106.002 (1989) does not set specific marine salinity discharge limits, careful monitoring is essential to protect marine ecosystems. Furthermore, the assessment reported that approximately 1,556 kg/day of sludge is generated from filter cleaning, with a concentration of 25 mg/L in the brine discharge, below Tunisia's 30 mg/L standard. Other key parameters assessed include water conductivity, heavy metal and chemical concentrations, pH levels, water temperature, and dissolved oxygen, whose solubility decreases as salinity rises. The oxygen saturation measured around 8 mg/L is acceptable, as aquatic life balance is significantly disturbed below 5 mg/L. An evaluation conducted in 2020 recorded temperatures of 30.5°C in summer and 22°C in winter, a pH of 8.1 (within the standard 6.5-8.5 range), and a suspended solids concentration of 19 mg/L (below the 30 mg/L limit). Other than that « the electrical energy consumption of the Djerba seawater desalination plant represents about 14% of the region's total electrical energy consumption. Also, the desalination plant is responsible for the release of a large quantity of brine amounting to 58 tones/day. Even though the desalination station has planned long pipes to carry out the rejects in depth, it remains essential to monitor the composition of this brine in advance to avoid a deterioration of the marine space». Otherwise, follow-up evaluations corroborate that the physicochemical and bacteriological composition of brine discharge complies with Tunisian waste discharge standards.

**Sfax Desalination Plant**

A governmental EIA has been published to assess the environmental impacts of the Sfax desalination plant and other planned facilities in the Sfax region (Gulf of Gabès). The project aims to inaugurate 4 desalination plants (Sfax, Djerba, Zarat, and Kerkennah) in the Gulf of Gabès, reaching a combined daily capacity of 381,000 m³ by 2030. The study of brine dispersion uses a combination of hydrodynamic modeling and environmental analysis to evaluate the gradual dispersion of the hypersaline plume. Findings indicate that salinity exceeds 45000mg/L within a 200m radius, surpassing the tolerance threshold of Posidonia seagrass, vital to marine biodiversity. The total impact on seagrass is estimated at a loss of 16.2 hectares—11.2 hectares due to underwater infrastructure and 5 hectares impacted by brine dispersion. The EIA also examines marine impacts from water extraction volumes across the entire Gulf, finding desalination plants' extraction represents only 0.6% compared to the Gulf's natural evaporation rate of 58.8 million m³/day, thus limiting overall impact. Furthermore, the Kerkennah plant, located 40 km away, does not intersect with Sfax discharge, minimizing cumulative effects. Nevertheless, mitigation measures are required to limit negative impacts on local artisanal fishing, such as optimizing discharge locations and implementing economic compensation mechanisms inspired by best practices, notably those used by British Gas in the region.

The marine discharge pipeline employs a multi-port diffuser head that dilutes brine to 48 400mg/L before settling on the seabed, significantly reducing local environmental impacts. However, this dilution strategy is not considered a mitigation measure but rather part of the project's original concept. To further dilute brine, two additional measures are proposed: 1) utilizing the brine discharge in Thyna's salt flats to recover and valorize salts, and 2) treating the brine at a nearby wastewater treatment plant. Nevertheless, these solutions are not feasible during the project's initial phase, making some impact around the discharge point inevitable. During operation, brine salinity will decrease to approximately 1000 mg/L beyond 750 meters from the discharge point, deemed safe for human activities. The definitive impact zone around the discharge is estimated at 5 hectares, relatively small compared to the region's total seagrass area. To further mitigate impacts, several measures are proposed, including installing artificial reefs to protect seagrass and prevent mini-trawl fishing—a practice already employed in the Gulf of Gabès. Anti-turbidity protections will be implemented during construction, and financial compensation for local fishermen is also considered. Water quality will be regularly monitored during construction and operation, measuring turbidity, pH, temperature, and conductivity. Post-operation monitoring will occur twice a year in the first year and annually for the subsequent two years at the discharge point. The EIA in Tunisia show positive outcomes and corroborated the engagement of Tunisia to use the best techniques to reduce the impact of seawater desalination on marine environment.

## *Opportunities to promote the viability of seawater desalination in the Mediterranean basin:*

### *a) Study of the development challenges of renewable energy-powered units based on recent techno-economic feasibility studies*

On a commercial scale, desalination plants powered exclusively by renewable energy sources are still relatively uncommon. However, several projects are demonstrating their feasibility. In Saudi Arabia, for example, a solar-powered facility using reverse osmosis has a capacity of 60,300 m³/day, expandable to 90,000 m³/day.

The Mediterranean countries have significant renewable energy potential to lower the carbon footprint of desalination activities, thanks in particular to: solar energy (photovoltaic and thermal), particularly abundant in the southern countries, with an estimated cost of between 5 and 6 US cents/kWh for photovoltaic; wave energy (with pilot projects underway in Spain and Italy to power desalination); wind and geothermal energy (the former is already in use in Greece). In this regard, it is worth noting that desalination based on membrane technology requires electrical energy from specific renewable sources (such as wind, marine energy, solar, etc.), while thermal desalination processes (such as MSF and MED) require thermal energy that only biomass, solar, or geothermal energy can provide. Thus, each desalination process requires suitable renewable energy sources. (see fig.1 in Annex)

Desalinating water for 100 to 200 million people in the Mediterranean region would require between 14.2 and 28.4 GW of photovoltaic capacity, which solar power could largely offset, particularly in southern countries given their high potential. Several studies have evaluated the costs of reverse osmosis (RO) desalination powered by solar energy, particularly photovoltaics (PV), compared to concentrated solar thermal power (CSP):

According to a 2015 GIZ study, a grid-connected RO-PV plant without battery storage costs between €0.84/m³ and €1.00/m³ in North African and Middle Eastern countries. This cost rises to €1.94/m³ for an off-grid RO-PV plant with battery storage. These figures remain higher than the average cost of conventional desalination plants, estimated at US$0.98/m³ according to a World Bank study (2019). However, the latter anticipates a continued decline in the costs of desalination powered by renewable sources.

According to the World Bank, in southern Mediterranean countries with high CSP potential, the cost of RO-CSP desalination is between US$1.50 and US$1.74/m³, compared to an estimate of €1.42/m³ by GIZ. Furthermore, the World Bank suggests that combining CSP and RO with thermal technologies such as Multi-effect distillation (MED) or Multi-stage flash (MSF) could further reduce costs in arid or semi-arid areas.

In Morocco, a study in the Agadir region shows that a 275,000 m³/day seawater desalination plant powered by solar PV and connected to the grid achieves a competitive cost of US$0.98/m³, compared to US$1.14/m³ for a plant combining PV, storage batteries, and connection to the national electricity grid. A RO-CSP plant, with storage and connection to the grid, has a cost of approximately US$1.13/m³. These costs are competitive compared to those of plants powered solely by the Moroccan national grid, which is still largely dependent on fossil fuels. In this context, powering a seawater desalination plant with stand-alone PV panels while connecting it to the grid (US$0.98/m³) currently seems the most financially optimal option for southern Mediterranean countries. However, most of these studies do not take into account the future evolution of the cost of desalination coupled with a fully decarbonized electricity grid. In Morocco, the gradual decline in the cost of solar electricity and the gradual decarbonization of the grid could lead to a lasting decrease in tariffs. This dynamic could call into question, in the long term, the viability of hybrid models (stations powered by autonomous PV panels coupled with a connection to the national electricity grid), particularly if the resale of electricity during peak periods becomes less profitable. It is therefore crucial to develop long-term energy management strategies for these installations. This involves designing sustainable financial models, capable of maximizing the resale of surplus electricity during peak periods, while purchasing electricity at preferential rates during periods of low sunshine. This type of strategy, based on the arbitrage between own production, storage and interaction with the electricity market, could offer a balance between decarbonization, economic viability and operational resilience. Future studies will have to integrate these dynamic hybrid models into their feasibility analyses. It is also recommended that techno-economic assessments focus on the viability of desalination connected to a national grid undergoing decarbonization.

Furthermore, the Spanish example is particularly edifying. With an electricity mix composed of approximately 77% low-carbon energy sources (renewables and nuclear) in 2024, Spain is a benchmark for evaluating the integration of solar power into a decarbonized grid. A recent study of several Spanish desalination plants establishes that the combination of stand-alone PV panels with a national grid connection constitutes, as in Morocco, the most efficient option from a technical and economic perspective. The study highlights that in the Segura basin, projects have been launched to increase seawater desalination capacity by adding solar PV panels, in order to meet agricultural needs while reducing the cost per cubic meter. At the Torrevieja plant (production: 120 hm³/year), the addition of 60 to 120 MW of photovoltaic panels allows to reduce energy costs from €0.21 to €0.17/m³ (-17%).

The system is based on a self-consumption model with the resale of surplus energy to the grid and the purchase of electricity when needed, which allows for maintaining a high proportion of solar energy while optimizing costs. The Valdelentisco and Águilas plants show similar results with PV installations ranging from 80 to 165 MW: In Valdelentisco, the energy cost drops from €0.25 to €0.20/m³ (-18%); and in Águilas, the same reductions are observed.

Simulations conducted for these three sites reveal a significant reduction in the average annual water cost:

- Torrevieja: from €0.4283 to €0.327/m³;
- Águilas: from €0.4856 to €0.396/m³;
- Valdelentisco: from €0.4445 to €0.378/m³.

In result, integrating PV solar energy dropped '' the cost of desalinated water by up to 24%, which makes the cost of water affordable for agricultural use in areas with productive agriculture, reaching less than 0.4 EUR/m3 in basins such as Segura''. These findings are in line with those observed in Morocco and tend to validate that coupling an autonomous photovoltaic plant with a connection to the electricity grid is currently one of the most efficient solutions for reducing desalination costs, while promoting the energy transition. However, desalination powered by connection to the decarbonized electricity grid could be financially more attractive in the long term, especially when the grid becomes completely decarbonized, which also saves the installation of expensive PV panels to power desalination plants semi-autonomously, as highlighted in the above-mentioned studies. Indeed, the Spanish context differs from the Moroccan one: although the Spanish electricity mix is highly decarbonized, it relies on several types of low-carbon technologies (wind, nuclear, etc.), on European interconnections and on high energy demand. Conversely, Morocco benefits from immense solar potential, a relatively low photovoltaic production cost and a lower energy demand. It is therefore likely that a fully decarbonized Moroccan electricity grid would eventually become more competitive than Spain's, given the general downward trend in solar electricity prices globally. These findings demonstrate the value of further research on plants connected to highly decarbonized grids, considering possible public support (subsidies, preferential tariffs, etc.). This approach would better steer policies toward sustainable models adapted to local realities, particularly for countries on the southern shore with enormous potential for harnessing solar energy. This in no way diminishes the strategic value of stand-alone desalination plants powered exclusively by solar energy, particularly in island or isolated areas with very sunny weather (e.g., the Canary Islands, Pantelleria, Greek islands), where they may prove more economically viable than grid connections. Furthermore, strategies should be identified to reduce the costs of storage batteries, in particular, by favoring sodium batteries which appear economically competitive, have a lower environmental footprint than other types of batteries and are compatible with seawater desalination. A regional study conducted on a Mediterranean scale highlighted the strategic importance of energy storage for desalination plants powered by autonomous solar energy. Storage, particularly via batteries, reduces overall costs (because without storage CAPEX in renewable energy could be significantly higher to reach the same volumes of water which contrasts to the quoted GIZ study), and it also plays a crucial role in the stability of the electricity system. Modulated control, combining batteries and pumping tanks, would make it possible to achieve up to 70% autonomy. However, this stability does not rely solely on batteries: maintaining stations connected to the national grid, combined with regional cooperation mechanisms and interconnection of grid infrastructures, appears essential to adjust electricity production and guarantee the resilience of the system. In the long term, for these grid-connected plants, priority must be given to the complete decarbonization of electricity mixes to reconcile affordable water production and energy transition.

In brief, sustainable decarbonization of desalination while optimizing costs requires:

- connecting plants to carbon-free national electricity grids;
- developing hybrid models with dynamic strategies for managing on and off-peak production;
- and adopting stand-alone solutions in island or remote areas, all accompanied by targeted public support mechanisms such as subsidies.

### *b) Study of the challenges of developing brine discharge treatment and recovery techniques from a MLD-ZLD perspective in the Mediterranean*

Several valuable minerals could be economically affordable to extract from seawater (see fig.2). That extraction is called ''brine mining'' and is done through MLD or ZLD approaches that enable to attenuate or eliminate brine discharge while harvesting minerals in a circular approach.

A study concretely demonstrates the technical, economic, and environmental feasibility of implementing ZLD and MLD systems to eliminate or reduce brine discharge and recover it in a circular approach. Conducted using data from the Eastern Mediterranean, it is of major strategic interest, as it highlights evidence for considering more sustainable desalination solutions at a regional scale.

The study compares two hybrid desalination systems using membrane technologies, FO and RO, from an MLD (Minimal Liquid Discharge) and ZLD (Zero Liquid Discharge) perspective. Both aim to reduce or eliminate brine discharge into the sea, while recovering freshwater and extracted by-products. FO is among the membrane technologies that has less energy consumption than many MLD technologies and is compatible with RO. In both configurations, FO is the most efficient technology for water recovery (approximately 80% in the MLD case and 98% in the ZLD case of seawater is desalinated), surpassing the recovery rate of reverse osmosis (RO) limited by osmotic pressure. The ZLD system, thanks to the integration of thermal processes such as Brine Concentrator (BC) and Brine Crystallizer (BCr), makes it possible to produce ultrapure water (<50 mg/L of dissolved solids – TDS), meeting the strict requirements of industrial sectors such as pharmaceuticals, microelectronics or high-precision processes. Conversely, the MLD system, based solely on membrane processes, produces water of lower purity (<500 mg/L TDS), but sufficient for standard domestic or agricultural uses. In terms of discharges, ZLD produces a solid salt residue (<1 $m^3$/day), while MLD generates a concentrated brine (<18 $m^3$/day), whose composition of sodium chloride, calcium carbonate, or magnesium chloride opens prospects for recovery in several industrial applications.

In terms of energy consumption, ZLD is more demanding (10.36 kWh/$m^3$) than MLD (6.74 kWh/$m^3$), due to the complexity of the added thermal processes.
From an economic perspective, the cost of water is slightly higher in ZLD (USD 0.79/$m^3$ compared to USD 0.72/$m^3$ for MLD), but the revenue generated is also higher, particularly thanks to the recovery of solid salt. Both systems are generally competitive compared to conventional brine disposal solutions (such as deep well injection). Net daily revenues are a bit higher for the ZLD (228.4 US$ per day) than for the MLD (195.3 US $ per day), due to the larger volume of recovered water and the ability to recover solid salt. These data show that the benefits of brine recovery outweigh the costs of the ZLD or MLD processes (see Fig. 4 and 5). Moreover, Sodium Chloride recovered by MLD-ZLD brine treatment could constitute raw material for sodium batteries. Further research would be relevant to evaluate the opportunity to harvest ''brine mining'' for sodium batteries which are very promising to foster a sustainable energy transition. Finally, $CO_2$ emissions, directly linked to energy consumption, are higher for the ZLD (6.81 kg $CO_2/m^3$) than for the MLD (4.35 kg $CO_2/m^3$), but lower than those of conventional thermal technologies. Combining them with renewable sources would further improve their environmental footprint and even lower costs.

However, it is important to highlight an important limitation of the presented techno-economic study: it is based on the analysis of a desalination unit operating in MLD/ZLD mode with a modest daily flow rate of 100 $m^3$/day. Although the results demonstrate that brine recovery is not only technically feasible but also economically beneficial and energetically optimized at this scale, uncertainties remain regarding the transposability of these results to larger-scale installations. Indeed, the extension of such strategies to industrial units raises the question of the scalability of the technologies, particularly in terms of membrane reliability, energy costs and performance stability under variable conditions. That said, a recent study qualifies this reservation and highlights the technical possibilities of integrating FO into large-scale hybrid desalination systems. This technology has several decisive advantages: it is compatible with reverse osmosis (RO), it consumes significantly less energy than thermal processes, as well as most membrane based technologies (see Fig.3), and it allows for a reduction in the operational costs (OPEX) of desalination units. In theory, it is technically feasible to treat only a fraction of the seawater, for example 35% via RO, while the remaining 65% would be treated by FO, which would allow high recovery rates to be achieved in an MLD approach, while limiting the osmotic pressure and therefore the energy requirements of the RO system. This strategy, already proven for the treatment of certain complex industrial effluents (mining waste, effluents from the textile and pharmaceutical industries, etc.), remains to be demonstrated for seawater. In the mentioned study, it is shown that hybrid systems integrating FO and RO can treat considerable volumes of water, with daily flow rates of 92 592$m^3$ for the seawater feeding the FO process, compared to 166 666$m^3$ for the RO process. The cost of produced water in this large-scale system varies between USD 0.71 and USD 0.84/$m^3$, depending particularly on the price of FO membranes and the local cost of electricity. These findings tend to confirm the technical and economic feasibility of using large-scale MLD strategies based on the FO-RO hybrid system.

Another important limitation to consider is the variability in the recovery potential of brines from seawater desalination, which are highly dependent on local geochemical characteristics—sometimes at the subnational level. Therefore, it would be relevant to accompany desalination projects with geographical and sectoral characterization studies to identify regions suitable for the installation of industrial brine recovery units. From this perspective, strategic environmental assessments (SEAs) could play a decisive role in long-term planning, particularly in countries on the southern shore of the Mediterranean, which are expected to rapidly develop green hydrogen projects based on seawater desalination. This point will be discussed in the following section.

### *c) Study of the challenges of developing desalination units to produce green hydrogen*

Green hydrogen plays a central role in the energy transition, particularly in key sectors such as cement and steel production. Produced by electrolysis of water using renewable electricity, green hydrogen generates no $CO_2$ emissions. Some energy transition scenarios estimate that approximately 2.3 giga tons (Gt) of hydrogen will be required every year to meet climate targets by 2050. However, concerns have

emerged regarding the water supply required for this production, with some media outlets highlighting that it could be expensive or put excessive pressure on water and energy resources. However, numerous scientific publications appear to temper these concerns. A peer reviewed study assessed the amount of water required to produce 2.3 Gt of hydrogen per year. According to this analysis, the production of 1 kg of hydrogen requires approximately 9 kg of water, which implies that annual production of 2.3 Gt of hydrogen would consume approximately 20.5 Gt (20.5 billion m$^3$) of water. This represents only 1.5 parts per million (ppm) of the Earth's available freshwaters. In other words, this amount of water is only 1.5 millionth of the world's total freshwater, which is a marginal quantity. Furthermore, it is important to note that green hydrogen will be produced solely from renewable energy sources, such as wind and solar, which consume little or no water. According to the considered study, producing hydrogen through water electrolysis could save up to 10 billion m$^3$ of fresh water, otherwise used by fossil fuels. The publication emphasizes that the water consumption to produce enough green hydrogen to meet industrial needs is lower than the water consumption of the agriculture, mining, and oil and gas sectors (see Fig.6).
Furthermore, the production of green hydrogen also requires a significant amount of renewable energy. It is in this sense that several Mediterranean countries, particularly those on the southern shore, are considering developing green hydrogen because they have vast potential for developing solar energy. However, Mediterranean countries, particularly those in the south, are facing water stress that is already alarming and will be aggravated by global warming. To overcome this obstacle, southern Mediterranean countries aspire to use seawater desalination to produce green hydrogen. The national green hydrogen development strategies of Algeria and Tunisia explicitly mention the use of desalination as part of this industry. Green hydrogen, which depends on freshwater for its electrolysis, can effectively be produced from desalinated seawater. Reverse osmosis, one of the most commercially mature desalination techniques, could be used to desalinate seawater needed to produce green hydrogen. However, this method only recovers 40 to 50% of the treated water, implying the withdrawal of 41 billion m$^3$ of seawater per year worldwide to produce 2.3Gt. This represents only 0.03 ppm of the Earth's available seawater which is a negligible amount.
From another perspective, desalination generates low energy demand compared to that required for water electrolysis. Reverse osmosis requires between 3.5 and 5 kWh of energy per m$^3$ of freshwater produced. Considering the estimated global hydrogen demand, this operation would add an annual energy consumption of 0.06 to 0.13% of the energy required for electrolysis, a marginal impact on the energy viability of hydrogen production. Besides that, the cost of desalination would vary between \$0.53 and \$1.50 per m$^3$ of freshwater produced, which would increase the cost of hydrogen by approximately \$0.01 per kg, which would represent 0.1% of the energy consumption of electrolysis and would increase the cost of hydrogen by \$0.02 per kg. Thus, even with this constraint, global targets of producing hydrogen at approximately \$2.00 per kg remain achievable, including the cost of seawater desalination. Although green hydrogen does not appear to require desalinating huge quantities of seawater, its production raises various technical, social and environmental issues. These questions will be addressed in a case study to put into relief the challenges associated with energy production through seawater desalination while considering the possibilities of integrating MLD or ZLD techniques.

### *d) Case Study - The Issue of Seawater Desalination to Produce Green Hydrogen in Tunisia from a ZLD and MLD Perspective*

Tunisia aims to produce 320,000 tons of green hydrogen per year by 2030, according to its national green hydrogen production strategy. To achieve this goal, a significant amount of seawater will need to be desalinated. Water electrolysis is the main process for producing green hydrogen, and each kilogram of hydrogen requires approximately 9 liters of water, not including the additional water required to produce hydrogen derivatives. Thus, to produce 320,000 tons of hydrogen (or 320 kt), including its derivatives, between 6.4 and 9.6 million cubic meters (Mm$^3$) of freshwater per year, according to the mentioned Tunisian national strategy. If a desalination plant has a production capacity of 100,000 to 500,000 m$^3$ of freshwater per day, it would be sufficient to cover the freshwater needs of green hydrogen production in Tunisia. For example, a plant with a capacity of 300,000 m$^3$/day could produce approximately 109.5 million m$^3$ of freshwater per year, significantly more than the 6.4 to 9.6 million m$^3$ required for hydrogen production. The largest desalination plants in the region achieves comparable figures.

The next step is to assess the technical feasibility of theoretically developing a green hydrogen project in Tunisia powered by a seawater desalination plant that minimizes or even eliminates the discharge of brine into the marine or other environment. At first glance, it should be noted that MLD or ZLD processes are more energy intensive than conventional desalination techniques and consume around 2 to 30 times more energy than reverse osmosis. However, the MLD-ZLD processes represent only a small fraction of the energy consumption required for the electrolysis of water to produce green hydrogen. According to recent research the production of green hydrogen requires approximately 40 kWh to 50 kWh per kilogram of hydrogen in optimistic scenarios. To produce 320,000 tons of hydrogen per year, this corresponds to a total energy consumption of 12 to 16 TWh per year. The energy consumption for desalination associated with an MLD or ZLD process in an optimal scenario surveyed in Eastern Mediterranean countries is between 3 and 10 kWh per $m^3$ of desalinated water, which correspond to an annual consumption ranging from 19,2GWh per year to 96GWh per year. Therefore, the energy consumption of MLD/ZLD desalination represents between 0.27% and 0,75% of the energy required to produce green hydrogen. From a global perspective, it is clear that the development of green hydrogen with or without desalination of seawater in MLD or ZLD process will require an enormous amount of renewable energy. Tunisia's annual energy consumption in 2014 is equivalent to the amount of electricity needed to produce 320,000 tons of green hydrogen! This project, although colossal, is feasible in Tunisia, which benefits from abundant sunshine and vast arid areas suitable for the installation of large solar PV or CSP power plants. In addition, Tunisia currently has an electricity production system that still relies little on renewable energy. As part of the energy transition, providing carbon-free electricity to local populations will be essential to foster the social acceptability of green hydrogen. Furthermore, the development of wind farms or solar photovoltaic power plants represents the highest financial cost of CAPEX in a green hydrogen project. It seems desirable to develop solar photovoltaic power plant projects independently of green hydrogen projects and to gradually increase the share of green energy in the electricity grid. The electricity thus produced could then be sent to desalination and green hydrogen production units, thus reducing costs while strengthening social acceptability. Indeed, one of the limitations of current research is that studies of carbon-free desalination projects in Mediterranean countries focus on the possibility of building stand-alone plants powered by wind or solar photovoltaic energy off the electricity grid. I believe it would be relevant to take the opposite approach, that is, to evaluate the possibility of integrating a greater share of solar energy or other renewable energy sources into the energy mix to promote carbon-free desalination and the development of MLD or ZLD technology. Furthermore, feasibility studies on green hydrogen projects coupled with desalination units powered by a «greener» electricity grid would reduce project costs, limit risks for developers, and lessen the environmental impacts of desalination plants.

In this sense, the issue of developing green hydrogen in the Mediterranean is inseparable from the renewable energy development issue as well as the technical feasibility to reduce brine discharge. Sustainable desalination through MLD or ZLD process, green hydrogen development, and green energy are 3 interdependent variables that must be considered from a systemic perspective. Energy is the key factor to decarbonize desalination plants, to minimize the environmental impact of saline discharges, and to produce green hydrogen. Green hydrogen production requires significant amounts of renewable energy, while desalination with a low liquid discharge or zero liquid discharge approach requires less energy input. However, green hydrogen could represent a window of opportunity to increase clean electricity generation capacity in Southern Mediterranean countries, increase the share of renewable energy in their energy mix, and meet the energy requirements of desalination plants operating in MLD or ZLD. If Southern Mediterranean countries effectively exploit their energy potential and develop optimized renewable production capacity, they would be able to produce green hydrogen while promoting sustainable desalination. For desalination plants operating in off-grid mode, it would be difficult to adopt an MLD or ZLD given the high energy demand of these processes. Unless major technological innovations enable high recovery rates and efficient conversion of brines into by-products, the development of a green energy infrastructure will remain an essential condition to enhance the sustainability of seawater desalination sector in the Mediterranean.

### *e) Socio-environmental issues associated with green hydrogen production*

The development of green hydrogen in countries on the southern shore of the Mediterranean, particularly in Tunisia, Algeria, Libya, Egypt, and Morocco, may raises social and environmental issues, particularly due to the use of seawater desalination as the water source required for hydrogen production. Even if these countries intend to rely on desalination to meet their green hydrogen ambitions, this approach presents some challenges that must be anticipated and managed. The first concern relates to potential conflicts related to water access. In Mediterranean countries, water is already a scarce and precious resource, particularly for the agricultural sector and domestic uses, given that Mediterranean countries, particularly those in the south, face chronic water stress. The rise of desalination projects exclusively dedicated to green hydrogen may accentuate social tensions and conflicts over water use, given that climate change is affecting the availability of drinking water for the population and irrigation water for farmers. Even if this risk is low as green hydrogen would use a small fraction of water resources compared to other sectors, social perception may be negative towards desalination projects that are not dedicated to basic social needs. To limit these impacts, several measures can be considered.

(1) At first glance, it is essential that desalination projects adopt a multi-use approach, meeting not only the needs of green hydrogen production, but also the needs of drinking water and irrigation. For example, by locating desalination plants near agricultural areas, it would be possible to exploit this water source to support irrigation, particularly in regions where crops suffer from water stress. This approach would make it possible to further enhance the value of desalination infrastructure and reduce tensions surrounding the allocation of water resources. The adoption of advanced technologies such as high-efficiency desalination systems using the MLD or ZLD process could play a key role in promoting the multi-use approach and social acceptability of green hydrogen projects. This technology allows for the extraction of a greater quantity of freshwater from seawater while significantly reducing the amount of brine discharged into the marine environment. By improving the efficiency of the facilities, this approach would help meet both green hydrogen and freshwater needs for domestic and agricultural uses.

Coupling green hydrogen production with MLD/ZLD technologies offers several advantages:

- Optimization of water resources: Additional water recovery: The use of innovative desalination techniques such as FO in MLD/ZLD systems allows for a maximum water recovery of 98%. This means that most of the water used in the desalination process can be reused, thus increasing the efficiency of water resource utilization. This water recovery can be used for agricultural, domestic, or industrial applications, increasing access to fresh water.
- Environmental and economic benefits: By increasing the efficiency of the desalination process, this approach helps reduce environmental impacts, particularly by reducing the amount of brine discharged into the environment. MLD technologies ensure discharge treatment that minimizes the ecological impact. The ability to recover minerals such as magnesium, calcium, and potassium from brine concentrates can provide an additional source of revenue and raw materials.
- Social benefits: Providing fresh water for agricultural and domestic uses through optimized water recovery from desalination processes can improve the social acceptability of the project, particularly in areas where access to water is limited.

Combining green hydrogen with advanced desalination technologies, particularly MLD/ZLD, presents a synergistic approach, not only producing hydrogen from a renewable energy source but also maximizing the use of water resources. This model could become a pillar of the energy transition, with a positive impact on water optimization, cost reduction, and environmental impact mitigation, while supporting local economic and social development. Moreover, it is crucial to conceive a uniform social and environmental impact assessment framework adapted to local realities. This framework should include an analysis of potential impacts on coastal ecosystems, the possibility to integrate MLD-ZLD in green hydrogen projects, possibility to enable multi-use of water desalination for domestic and agriculture use, and rigorous monitoring plans of long-term cumulative impacts. Such an approach would help anticipate potential tensions and promote the implementation of integrated desalination projects, beneficial both for green hydrogen production and for the needs of local communities.

(2) Secondly, it is suggested that, in case MLD or ZLD associated with green hydrogen projects are not technically and economically feasible, Mediterranean countries develop plans to develop future seawater desalination plants dedicated to domestic and agriculture use notably by using revenue gained through green hydrogen projects or other financing sources. Governmental plans could enhance social acceptability if civil society is aware that future desalination projects are not only dedicated to hydrogen development.

### *f) Recommendations for strengthening the regional framework and associated policies to promote sustainable desalination activities in the Mediterranean region*

Reflecting the environmental and energy challenges posed by desalination, 2 options seem considerable to uphold the regional governance of the sector in a sustainable development vision. (1) As a first option, consideration could be given to design a specific protocol on desalination that harmonizes technical norms as well as to standardize environmental and socio-economic impact assessments (ESIAs) and encourages the reduction or even prohibition of brine discharges wherever possible. The Mediterranean is a semi-closed sea, and the environmental effects of brine discharge are likely higher than in the Ocean or open seas. That represents another key argument inviting to reform the regional framework. Adopting a new protocol, under the auspices of the Barcelona Convention, could strengthen regional cooperation and ensure a harmonized approach, notably by making mandatory:

The assessment of the possibilities of integrating advanced technologies (ZLD, MLD, brine mining) to limit brine discharges, particularly for desalination plants supplying green hydrogen production.

The integration of renewable energy into all desalination projects as a condition of financing.

A multi-use approach integrating agricultural and domestic needs into all types of desalination projects, particularly with regards to green hydrogen, or at least, if a multi-use isn't feasible, plan to develop seawater desalination plants for agriculture and domestic purposes and not only for green hydrogen.

A robust monitoring framework with long-term follow-up requirements alongside transboundary impact assessments, and cumulative impact assessments.

Uniformized SEAs to identify suitable areas for ''brine mining''.

The development of this hypothetical protocol nevertheless infers several considerations presented here from the perspective of opportunity and risk analysis:

### *Opportunities for regional cooperation:*

Creation of a common framework: A standardized protocol would avoid regulatory fragmentation and facilitate dialogue between States. It would allow, for example, the development of a standard ESIA and SEA template that all desalination plants would be required to follow in a binding, rather than voluntary, manner. It would harmonize standards of brine discharges, ecological impact, monitoring indicators, and prevent social tensions.

Strengthening governance: A mandatory ESIA would limit environmental and social dumping and improve the coordination of desalination and renewable energy projects, thereby reducing conflicts over water and energy resources. It will be appropriate to grant a greater role to competent regional organizations, particularly in reviewing and disapproving national ESIAs if minimum socio-economic and environmental criteria aren't met, in order to eliminate the risk of legal polarity between countries of the North and South and avert socio-environmental dumping. Binding measures could only be considered when minimum socio-environmental criteria are not met. However, it is important to define these criteria through constructive dialogue and around a shared vision of sustainable development.

Access to international financing: A harmonized framework would give projects greater credibility with institutions such as the World Bank, facilitating international financing and cross-border partnerships. Following a standardized ESIA format could be a prerequisite for obtaining funding.

### *Risks of hindering cooperation:*

Perception of a loss of sovereignty: Some countries may perceive the obligation to follow similar ESIAs at the regional level as external interference, hindering their adherence. The heterogeneity of national socio-economic situations makes a uniform approach difficult. However, regional collaboration can be strengthened by formulating subregional objectives that reflect local realities and developing ESIAs in a standardized and contextualized format in collaboration with states and other stakeholders.

Bureaucracy and increased costs: Overly rigid or onerous requirements (e.g., ZLD, brine mining) could be perceived as barriers to investment, slowing the development of critical infrastructure. However, in an era of technological breakthroughs, many extracted minerals have market value. Regional incentives and preliminary studies of desalination sites could proactively identify suitable locations for brine mining. The Sea4Value initiative is an example of good practice in the Mediterranean.

### *Phased and flexible implementation can address these risks through the following measures:*

Differentiated approach: Adapt requirements according to the scale of the project (national rules for small projects, harmonized regional framework for large projects). Also, contextualized guidelines could be helpful in the sense that the applicability of ESIA and the definition of environmental quality threshold should be considered regarding the level of development and capacity of the countries.

Support mechanisms: Creation of a support fund to finance EIAs in developing countries and a shared database on environmental impacts and best practices.
Gradual and incentive-based implementation: A five to ten-year transition with progressive incentives and sanctions would allow for gradual adoption without slowing investment.

Key role of regional organizations: UNEP/MAP and other relevant institutions could support states in implementing the protocol while supporting pilot projects that comply with the new standards.

Consequently, a Mediterranean protocol on desalination could strengthen cooperation and ensure high environmental standards. Flexible and phased implementation would help avoid rejection by some states. Harmonizing EIAs would promote access to finance and facilitate the transition to sustainable desalination integrated with renewable energies.

(2) A second option could be to strengthen UNEP/MAP Guidelines rather than embarking on the lengthy process of creating a new binding protocol under the Barcelona Convention. The proposed update of UNEP guidelines means to introduce a standardized ESIA template to be applied uniformly to desalination projects across the Mediterranean. In this sense, the ESIA would go beyond traditional environmental studies to include:

- An assessment of the multi-use potential of seawater desalination, such as meeting domestic needs, supporting agriculture, and supplying green hydrogen production.
- A techno-economic study of incorporating advanced brine management solutions like Minimal Liquid Discharge (MLD) and Zero Liquid Discharge (ZLD) into major desalination projects—especially those linked to green hydrogen production.
- An assessment of transboundary potential marine pollution of seawater desalination facilities.

To encourage adoption of the revised guideline, meeting this ESIA standard could be set as a condition for receiving funding from international donors, regional capacity building initiatives, development banks, and climate financing mechanisms for any desalination project or program. This path might initially be more appealing to Mediterranean countries because it avoids the political sensitivity and legal hurdles of negotiating a new protocol. It could also be folded into current frameworks relatively quickly, offering more flexibility and a lower barrier to entry. That said, without binding requirements—and without the backing of financing programs, capacity-building initiatives, and technical support to expand renewable energy use and roll out MLD/ZLD—achieving truly sustainable desalination across the region would remain difficult. While a dedicated protocol (the first option) would set clearer, enforceable standards, this second option could work as a practical interim step—helping to build consensus, trial a harmonized ESIA process, and pave the way for a future legally binding Mediterranean desalination protocol.

## CONCLUSION

To conclude, this paper dealt with the legal, technical, economic, and socio-environmental aspects of seawater desalination in the Mediterranean. It also focused on its linkage to the green hydrogen sector, developing the reflection on a ''seawater desalination-green hydrogen-renewable energy'' nexus. The report has shown that while desalination is a strategic solution to address water scarcity, it also poses significant ecological risks, especially from brine disposal. It is suggested to manage those risks through coordinated governance, improved technology, and stronger regional cooperation.

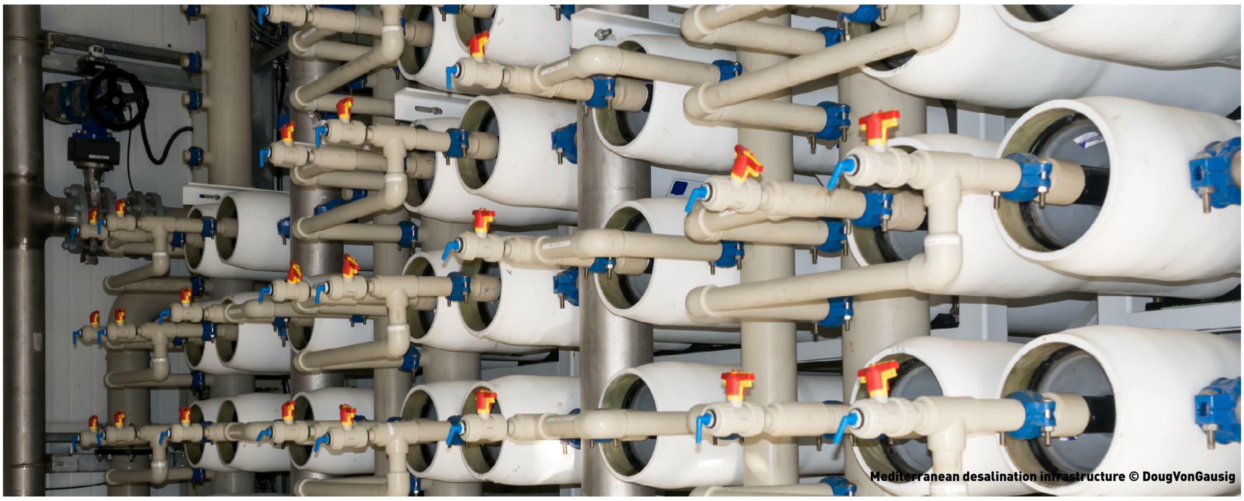
To strengthen regional governance of desalination in the Mediterranean, especially regarding green hydrogen projects, it is essential to take a varied, phased, and integrated approach. A blanket ban on brine discharges is not realistic or desirable in the short term. Instead, obligations should be tiered, with stricter requirements for large-scale projects or those in sensitive areas, notably to protect Posidonia seagrass meadows and marine protected areas. Green hydrogen projects should be made conditional on the integration of brine-reduction or brine-valorization technologies (MLD-ZLD), depending on economic and environmental feasibility studies, and all desalination projects should assess the potential for brine mining and multi-use applications.

In this context, incorporating sustainable desalination projects into maritime spatial planning (MSP) is crucial. MSP should identify, through a proactive approach, areas suitable for brine mining, guiding desalination projects toward circular, low-discharge models. SEA have a central role to play in this process: they not only help locate sites with high brine-valorization potential but also assess the feasibility of multi-use facilities (such as hydrogen production, domestic water use, irrigation, etc.), thereby increasing both social acceptability and long-term sustainability. To ensure regional consistency, it would be relevant to articulate these requirements in a new Mediterranean desalination protocol under the Barcelona Convention. Such a protocol could include specific provisions mandating technology transfer and the systematic consideration of possible MLD/ZLD solutions—especially for green hydrogen projects—while also establishing harmonized standards on salinity thresholds, discharge technologies, and other parameters as chemical contaminants. Additionally, strengthening the regional framework seems essential to promote cumulative impact assessment and transboundary environmental assessment.

Another strategic pillar is the large-scale development of solar energy, particularly abundant in Southern Mediterranean countries. This expansion should not be tied exclusively to desalination projects, but should proceed in parallel through regional partnership agreements, aimed at decarbonizing national grids, using surplus energy for export and green hydrogen production, and enabling the growth of high-environmental-performance desalination units. Achieving this will require improved regional cooperation, including the development of electrical interconnections, to support an inclusive, circular and sustainable development that preserves marine ecosystems.

From another standpoint, further research should be led to identify opportunities to foster multi-use approach notably to use desalinated water for irrigation at a competitive price. Market entry of minerals extracted from brine should also be more evaluated to address potential future barriers that might hamper the scaling of MLD-ZLD approach. Other countries are interested in harvesting brine mining to recover valuable minerals and metals. In my opinion, countries should prioritize brine mining in semi-enclosed seas like the Mediterranean and the Red Sea, where desalination impacts are more concentrated than in open oceans such as the Atlantic. Mediterranean States should create regional trade arrangements that grant preferential market access to minerals recovered from Mediterranean ''brine mining activities'', rather than ''brine sourced'' from different marine zones. Likewise, synergies between sodium battery storage and desalination powered by renewables as well as techno-economic feasibility harvesting Sodium Chloride from brine to use it as raw material for Sodium battery is another interesting axis of research. In this perspective, it is important to consider the legal governance at regional level of desalination that is supposed to reflect new technical, economic, and socio-environmental factors that shifted since Barcelona Convention elaboration.

# CHAPTER II. THE ECONOMICS OF DESALINATION AND SUSTAINABLE DEVELOPMENT MODELS


Mediterranean desalination infrastructure © DougVonGausig

## Chapter II Introduction

Although the desalination sector provides massive amounts of water, it entails significant economic costs. The infrastructure and related operations are expensive and can place a financial burden on Mediterranean municipalities. . In fact, the whole life cycle of desalination units is expensive and highly sensitive to external economic factors such as fuel price fluctuations and evolving technology costs.

Both capital and operational expenditures are substantial, and if desalination systems are not carefully designed, the resulting water prices may prove economically unsustainable. This economic dimension is central to achieving sustainable desalination, as financial viability is a key factor in the sector's long-term resilience.

This chapter evaluates the economic feasibility of desalination, particularly when integrated with other activity sectors such as agriculture. Concretely, it explores how synergies between desalination and agriculture can improve crop yields in water-scarce areas, potentially fostering integrated development models that enhance overall economic viability.

From a public perspective, an important question arises: what is the willingness to pay for desalination activities? Understanding societal economic acceptance is essential for sustainable development models. For many households, water bills are already a concern. Understanding how people perceive the equity and usefulness of desalination is key to designing policies they will support. The third article in this chapter investigates public perceptions of the sector's acceptability in order to uncover the dynamics of trust and economic acceptance that determine the success of desalination projects.

The final two articles take a broader, country-level approach, offering cross-national comparisons across 11 Mediterranean countries. Using econometric models that incorporate a range of endogenous and exogenous variables, including demographic trends, national GDP, the share of renewable energy, and carbon dioxide emissions, these studies provide valuable insights into how national economic contexts shape desalination strategies and their role in sustainable water management.

# ASSESSING THE ECONOMIC VIABILITY OF DESALINATION IN SELECTED MEDITERRANEAN COUNTRIES: HOW CAN IT CONTRIBUTE TO A SUSTAINABLE FUTURE?

AUTHORS : SAMIR MALIKI, NATHALIE HILMI, MOURAD KERTOUS, ABDELHADI BENGHALEM


Aerial view of the treatment plant.© Rommel Gonzalez


## Abstract

Desalination has become a critical solution to water scarcity in the Mediterranean region, driven by climate variability, population growth, and economic demands. This study evaluates the economic viability, environmental sustainability, and policy implications of desalination across 11 Mediterranean countries using panel data (2000–2025) and regression models (FE, RE, Pooled OLS). Key findings reveal that population density and renewable energy adoption significantly influence desalination capacity, while ocean health correlates negatively with reliance on desalination. Countries like Israel and Algeria demonstrate strategic advancements in desalination despite lower GDP, leveraging low energy costs and large-scale infrastructure. However, environmental challenges, such as brine disposal and $CO_2$ emissions, persist. To improve sustainability, the research emphasizes the necessity of integrated policies that include marine conservation, circular economy concepts, and renewable energy integration. According to the study's findings, desalination may be used to alleviate water scarcity while minimizing ecological trade-offs when combined with renewable energy and appropriate environmental governance.

## INTRODUCTION

Water is a vital resource, but one that is unevenly distributed and subject to increasing pressure, particularly in arid and semi-arid regions such as the Mediterranean basin. This area, characterized by a climate often marked by drought and high variability in precipitation, is faced with an ever-increasing demand for water due to the combined effect of population growth and economic activity.

Today, seawater desalination is an essential response to the growing challenges posed by the scarcity of freshwater resources. However, this process, while indispensable, raises major issues, notably the high energy consumption of the installations and the environmental impact of brine discharges.

Desalination presents a viable solution for addressing water scarcity in Mediterranean countries, particularly through innovative technologies that enhance sustainability. These countries can improve water security by integrating renewable energy sources and advanced desalination methods while minimizing environmental impacts. The scarcity of freshwater resources has made desalination an attractive solution for many Mediterranean countries, offering a way to produce potable water from seawater. However, desalination remains an energy-intensive process with high operational costs and environmental impacts. Determining whether desalination is economically viable and environmentally sustainable requires carefully analyzing both short- and long-term effects, especially considering the Mediterranean's unique climatic, economic, and environmental context.

Addressing acidification in the Mediterranean requires an integrated approach that includes global $CO_2$ mitigation efforts, regional environmental regulations, and local conservation initiatives (Ali, E et al., 2022). The Mediterranean countries collaborate through institutional frameworks like the Barcelona Convention and its related protocols to combat pollution and acidification, focusing on reducing carbon emissions and controlling nutrient loading for instance (UNEP/MAP, 2017).

In this chapter, we will test through regression models (FE, RE and Pooled) on panel data of four periods (2000, 2010, 2020 and 2025) for 11 selected countries of the Mediterranean region, using six variables depending on data availability and reflecting the region's demographic, economic and environmental challenges.

Given the growing number of plants being installed since 2020 in particular, we have dedicated the first section, following an introduction, to a review of the multidisciplinary literature that has attempted to economically evaluate the seawater desalination process in these different countries. The energy component and financial feasibility of setting up and operating these desalination plants are explained in the next section. The methodology and proxies selected based on data availability are examined in the fourth section. The results are discussed in section five and policy implications are identified in the last section.

### *Literature review*

Previous research on desalination has primarily focused on technical and environmental aspects. For example, (Ghaffour et al.,2013) highlight the technological advancements in desalination and their implications for sustainability, while Bouzguenda et al. (2019) discuss the environmental impacts, such as greenhouse gas emissions and brine discharge. Economically, desalination remains a debated topic due to its high costs and energy requirements, as Karagiannis and Soldatos (2008) examined. Integrating photovoltaic solar energy with seawater desalination can reduce energy costs by 50% and overall water production costs by 25%, making desalination economically viable in Mediterranean semiarid regions facing water scarcity challenges (Gómez et al.,2023). In the same context, energy storage costs for desalination are as low as 0.19 EUR/m$^3$, with 75% of sites not exceeding 0.23 EUR/m$^3$ (Ganova, D. et al., 2019), suggesting economic viability for large-scale PhotoVoltaic powered Reverse Osmosis (PV-RO) desalination. Optimistic research highlights, by assessing the financial feasibility of desalination using a feasibility index (Gao L. et al., 2017), agree that countries, including those in the Mediterranean, are likely to find desalination increasingly viable by 2050 as production costs decline and water prices rise. Mahmoudi et al. (2023) review challenges such as high salinity in the Mediterranean Sea and propose renewable-powered desalination as a sustainable alternative.

From an Econometric view, a study of cost factors and economic sustainability of desalination by Greenlee et al. (2009) suggests that economies of scale can reduce costs in the long run. However, there needs to be more research concerning the integration of desalination within a circular economy framework, where resources are recycled and reused, potentially lowering costs and environmental impact.

The paper seeks to address this gap by applying economic modelling and circular economy principles to assess desalination in the Mediterranean context. The example of Algeria can illustrate the policy of desalination. In a study that examines the impact of water subsidies and desalination on sustainable resource management, the results indicate that while subsidies help ensure water affordability and accessibility, they often lead to over-extraction of groundwater and inefficient water use (Boubou-bouziani, N., & Maliki, S. B.,2014). Desalination, although a promising alternative, poses environmental concerns such as carbon emissions and brine disposal (Maliki S.B et al.,2024). The study suggests that aligning subsidy policies with sustainability goals and investing in renewable energy-powered desalination could enhance resource management and mitigate environmental impacts. Studies have been conducted to assess the economic feasibility of desalination in the Mediterranean area, namely in nations like Greece, Cyprus, and Israel. A Zero Liquid Discharge (ZLD) desalination system has demonstrated encouraging outcomes, requiring just 20.23 kWh/m$^3$ of energy and having a high recovery rate of 99.19%. This technology is equivalent to deep-well injection and land application options, and it is at least 3.22 times less expensive than evaporation ponds. Cyprus and Greece reveal differing degrees of profitability in the profit from the distribution of desalinated water (Panagopoulos, A.,2022).

One important element in improving the desalination facilities' economic viability is the use of renewable energy sources, like photovoltaic solar energy. In Spain, saltwater desalination treatment facilities powered by solar energy have reduced energy costs by around 50% and final water production costs by 20–30%. In addition to cutting operating expenses, this integration supports sustainable development objectives (Martínez, G., & Martín, M.,2023). Comparably, solar-powered desalination in Portugal has been demonstrated to lower unit production costs by around 33%, making it a financially feasible alternative to the country's present water tariffs (Apolinário, R., & Castro, R.,2024).

The economic potential of these technologies is demonstrated by a comparison of ZLD and MLD systems in the Eastern Mediterranean. ZLD systems are more profitable when both water and solid salt are provided, although MLD systems need less both money and energy. These systems have substantial economic potential, support the circular economy, and provide a useful substitute for underground water sources (Panagopoulos, A., & Giannika, V., 2022). One of the main concerns is the effect desalination has on the environment, especially when it comes to brine disposal. However, by creating mixed solid salt and accessible freshwater, ZLD system improvements reduced some of these effects. Compared to more conventional disposal techniques like evaporation ponds, these systems are far less expensive, making them economically feasible. The profitability of these systems is enhanced when both freshwater and solid salt are sold (Panagopoulos, A.,2021). With continuous research and development aimed at enhancing the technologies' economic and environmental features, desalination in the Mediterranean area has a promising future. To manage the water crisis in sustainable ways, it is anticipated that the incorporation of renewable energy sources and improvements in desalination techniques would be essential (Ganora, D., et al., 2019). In conclusion, incorporating renewable energy sources and using cutting-edge desalination technology greatly improves the economic feasibility and sustainability of desalination in Mediterranean countries. In addition to making desalination economically viable, these initiatives support more general environmental and sustainability objectives.

## *The Mediterranean context: opportunity and challenge*

### *Seawater desalination capacities*

Analyzing the statistics on seawater desalination in the Mediterranean reveals major disparities between countries. Spain has the largest total desalination capacity of 5,597,077 m$^3$/d, followed by Algeria (2,438,401 m$^3$/d) and Israel (2,212,997 m$^3$/d). These countries, which depend heavily on desalination to meet their water needs, have developed important infrastructures, as they suffer from many deficits, as in the case of Algeria, which ranks 16th among the most deficient countries in the world, with a per capita availability of less than 300 m3/year/inhabitant. Egypt stands out for its high number of plants (647), although its total capacity (2,563,987 m$^3$/d) is close to that of Israel, suggesting smaller plants. On the other hand, France and Italy have a significant number of plants (67 and 241, respectively), but their total capacity is well below that of the most advanced desalination countries, as shown in Figure 1.

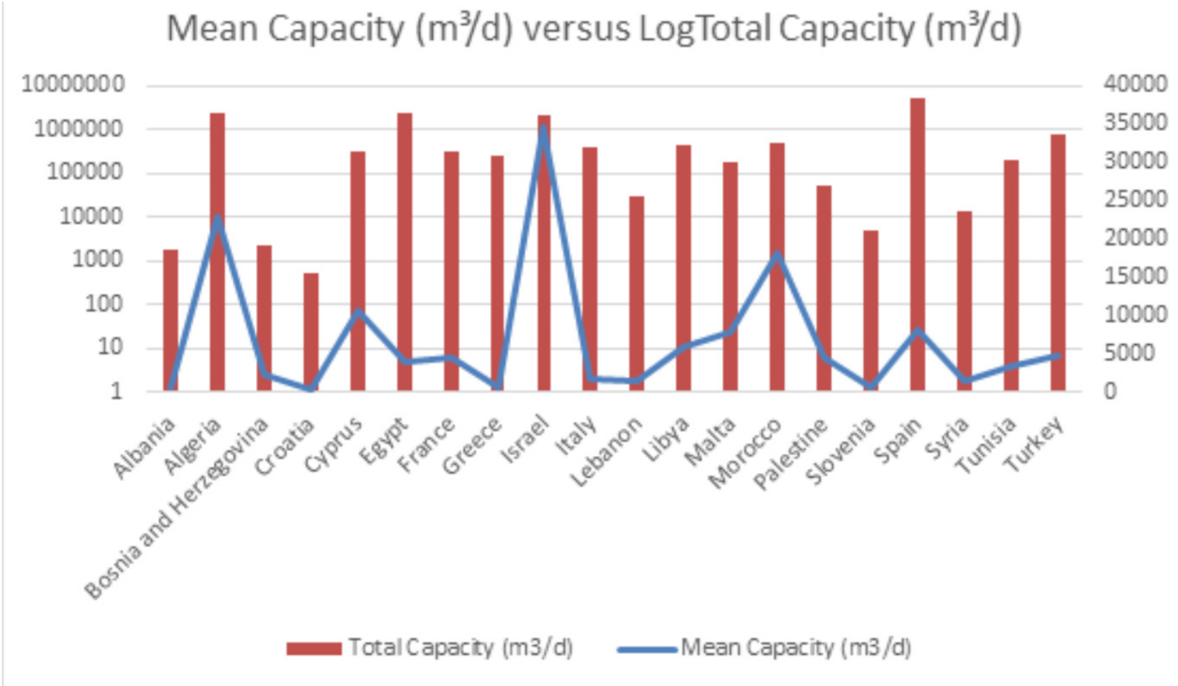



**Figure.1** *Mean Capacity (m³/d) versus LogTotal Capacity (m³/d)*
*Source: Authors' calculation*

The average capacity per plant shows Israel stands apart as it uses large, modern, and effective plants that average 34,578 m³/d per plant. Algeria and Morocco also have high average capacities (23,003 m³/d and 18,116 m³/d per plant, respectively). On the other hand, Greece (687 m³/d per plant) and Slovenia (694 m³/d per plant) have smaller systems and much less use of desalination in total.

In the same way, a comparison based upon desalination methods, shown in Figure 2, reveals significant effects for some countries. Reverse Osmosis (RO) is the leading method and has been adopted by most of the countries in this report. Israel has a truly remarkable installed capacity of 45,192.92 m³/day which demonstrates and highlights the overall technological pre-eminence of the country in this particular field of activity. The CLEAR dominance of RO is also evident in Algeria (26,321 m³/day), Egypt (3,845 m³/day), and Morocco (18,686 m³/day), where it shows appeal for maximum cost efficiency in these arid zones. Otherwise, thermal technologies reveal a wider heterogeneity of use. Multi-Effect Desalination (MED) reveals significantly lower uptake in Algeria (3,76857 m³/day) and Egypt (3,564 m³/day), which were also limited and suitable only for specific tasks requiring special technological specifications. The Multi-Stage Flash (MSF) still has uptake, but its exact extent is less clear, except for Algeria (23,202 m³/day) and Libya (18,835 m³/day), which are likely due to specific requests.

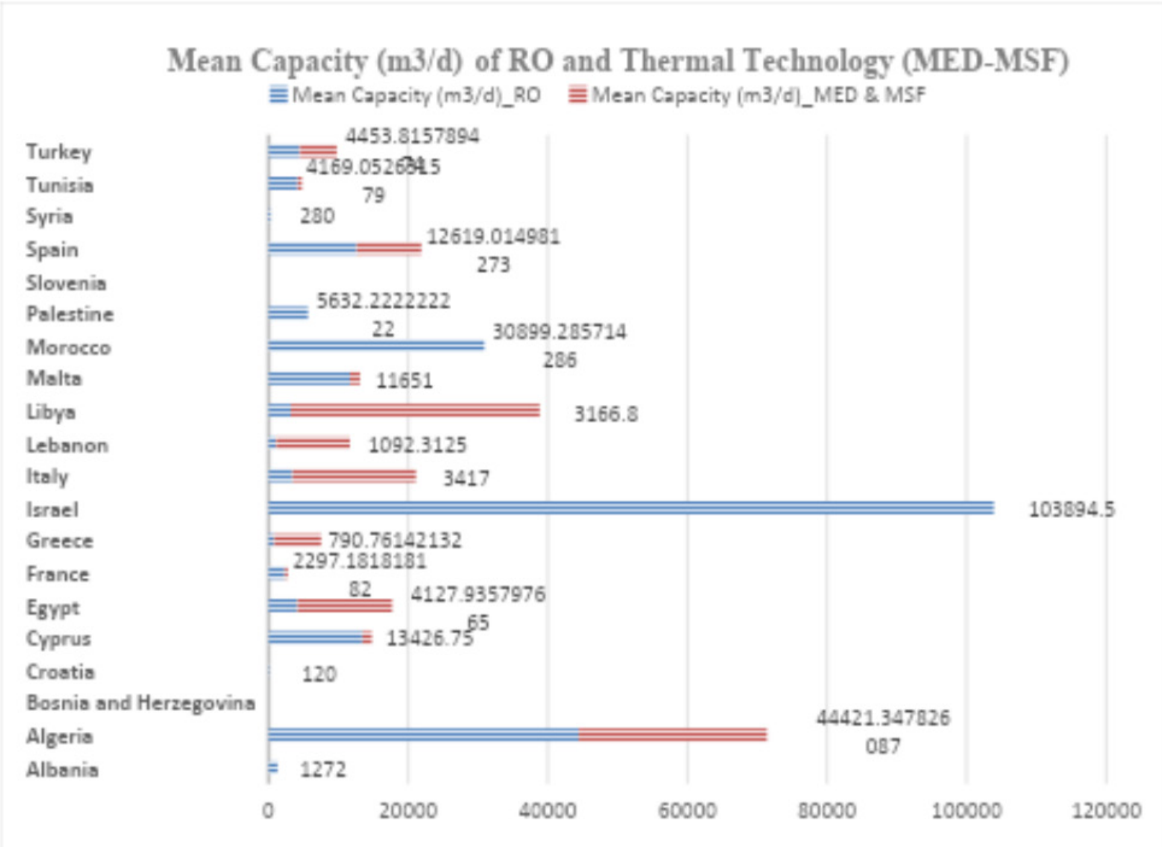



**Figure.2** *Mean Capacity (m3/d) of RO and Thermal Technology (MED-MFS)*
*Source: Authors' calculation*

This technological distribution probably reflects the combined influence of several factors:

1. The technological maturity and energy efficiency of RO
2. Differential operating and maintenance costs
3. Geographical specificities and the quality of available water resources
4. National policy orientations and technological investments.

The hegemony of RO suggests its optimal suitability for majority needs, while the persistence of thermal technologies in certain contexts indicates their relevance for specific applications or specific local configurations. These differentiated technological choices illustrate how water constraints are addressed differently according to national or more local contexts.

## *Desalination and Energy*

An analysis of the GDP of the countries studied sheds light on the disparities in desalination development and highlights the impact of production costs, particularly the price of electricity, on the economic viability of this technology. Countries with high GDPs, such as France ($2,782 billion), Italy ($2,010 billion), and Spain ($1,500 billion), have considerable financial resources, but their commitment to desalination varies. Despite moderate electricity prices ($0.152/kWh), Spain has developed a large desalination capacity of 3.44 million $m^3$/d. France and Italy, on the other hand, although economically strong, have relatively modest desalination capacities due to less reliance on this technology and other sources of water supply.

| Countries | Number of plants | Electricity price for businesses ($/kWh) | GNI per capita (current US$) | GDP per capita, PPP (current international $) |
|---|---|---|---|---|
| Egypt | 516 | 0,037 | 3840 | 18524,83 |
| Spain | 268 | 0,152 | 32940 | 53229,92 |
| Greece | 197 | 0,204 | 22320 | 41181,99 |
| Turkey | 76 | 0,117 | 11730 | 42326,16 |
| Algeria | 46 | 0,035 | 4950 | 16824,48 |
| Italy | 26 | 0,578 | 38610 | 57893,40 |
| Cyprus | 24 | 0,319 | 32960 | 57204,58 |
| Israel | 20 | 0,148 | 54280 | 53401,17 |
| Tunisia | 19 | 0,113 | 3850 | 14009,51 |
| Lebanon | 16 | 0,164 | 3730 | 12574,83 |
| Libya | 15 | 0,009 | 5940 | 13848,79 |
| Malta | 15 | 0,161 | 34500 | 63074,74 |
| Morocco | 14 | 0,106 | 3760 | 9842,88 |
| France | 11 | 0,205 | 45440 | 58317,82 |
| Palestine | 9 | 0,148 | 4310 | 5950,02 |
| Albania | 1 | 0,131 | 7680 | 21259,79 |
| Croatia | 1 | 0,16 | 20590 | 45595,62 |
| Syria | 1 | 0,008 | 770 | 4650,06 |

**TABLE 1**

**Number of plants Vs Electricity price for businesses, GNI and GDP (2023)**

*Source : Authors' calculation using Plan Bleu data and WDI for GNI and GDP, 2023*

Table 1 shows the key factors in assessing the economic potential of large-scale desalination projects taking in consideration the electricity costs. Countries with low electricity prices, such as Libya ($0,009/kWh), Syria ($0,008/kWh), Algeria ($0,035/kWh), and Egypt ($0,037/kWh), may be better equipped to sustain widespread desalination without passing significant costs on to consumers.

The statistics reveal that countries with low electricity costs, such as Algeria, Egypt, Libya and Syria, have a relative advantage by establishing large-scale desalination with little outlay to individual consumers, but this comes with the caveat of significant state subsidies, which raises urgent questions about budget sustainability and environmental protection. Furthermore, the existence and geographic distribution of power generation facilities limit the integration of desalination plant capacity into the national grid. Egypt exemplifies a country with an extensive power generation system with 516 desalination plants installed, which adds to a significant increase in the coastal desalination capacity. Meanwhile, countries with little energy infrastructure, such as Syria, Croatia, and Albania, will find that operational ability is impacted to a greater degree. Desalination has become an urgent alternative to water deficit, increasingly exacerbated by climate change, population growth, and economic development. As an example, Israel's position as the global leader in desalination is not just attributed to high costs of energy, but rather a mix of innovation and the development level of income was crucial.

In contrast, Spain and Cyprus have also advanced significant desalination efforts in economically strong coastal tourism areas with an adequate GDP and appropriate policies to absorb the electricity cost. Countries in North Africa, including Algeria, Morocco, and Tunisia, have expanded desalination capacity in response to severe arid conditions and increasing demand for potable water (population growth). However, their comparatively low gross national income and moderate levels of purchasing power parity suggest that sustaining these investments will likely require continual external support or structural reform of existing subsidy regimes (Maliki, S. B. et al, 2024)

## METHODOLOGY AND VARIABLES

The econometric analysis will employ regression models to assess the determinants of desalination in eleven selected Mediterranean countries: Algeria, Egypt, Greece, Israel, Italy, Libya, Morocco, Palestine Spain, Tunisia and Turkey with panel data of four periods (2000,2010,2020 and 2025) using the R statistical package.

$$DES_{it} = \beta_0 + \beta_1 RE_{it} + \beta_2 CO2_{it} + \beta_3 GDP_{it} + \beta_4 OHI_{it} + \beta_5 POPD_{it} + \varepsilon_{it}$$

Where:

- $DES_{it}$: Installed desalination capacity (million cubic meters per year, Mm³/y) for country i at time t. (dependent variable)
- $RE_{it}$: The percentage of a country's or region's total energy consumption that comes from renewable sources
- $CO2_{it}$: Carbon dioxide emissions (total) excluding LULUCF (% change from 1990)
- $GDP_{it}$: Gross Domestic Product per capita (USD) for a country
- $OHI_{it}$: the overall health of marine ecosystems, typically on a scale from 0 to 100. for a country
- $POPD_{it}$: the number of people living per unit area, typically expressed as persons per square kilometer for a country
- $\varepsilon_{it}$: Error term capturing unobserved factors affecting the desalination

The Panel data analysis offers significant advantages for this study, as it combines cross-sectional observations (countries) with temporal dimensions (2000–2025). The three models employed—Pooled OLS, Fixed Effects (FE), and Random Effects (RE)—each serve distinct analytical purposes in understanding desalination determinants:

- Fixed Effects (FE) models control for country-specific, time-invariant factors such as geographic constraints and institutional policies, which are essential in the Mediterranean context where governance and resource endowments vary greatly (Plan Bleu, 2024).
- Random Effects (RE) models assume that unobserved heterogeneity is uncorrelated with explanatory variables, allowing for more efficient estimation when this assumption holds. The Hausman test was used to determine the appropriateness of RE versus FE models, following econometric best practices (Papapetrou et al., 2017).
- Pooled OLS serves as a baseline but does not account for panel structure, highlighting the necessity of FE/RE adjustments given the diversity in energy policies and water scarcity levels across the region.

| Variables | Aim | Source |
|---|---|---|
| Desalination Capacity (Mm³/y) | Annual desalination capacity in Million cubic meters per year | Several sources:<br>Amcham.org.eg<br>Planbleu.org<br>Middle East Institute<br>Palestinian Water Authority (PWA)<br>UNICEF<br>EU Blue Economy Observatory |
| Renewable Energy Share (%) | Refers to the percentage of a country's or region's total energy consumption that comes from renewable sources such as solar, wind, hydro, biomass, and geothermal energy.<br>This metric is crucial for understanding the transition to sustainable energy systems. | World Development Indicators |
| CO2 Total (tons) | Carbon dioxide (CO2) emissions (total) excluding LULUCF (% change from 1990) | World Development Indicators |
| GDP per Capita (USD) | is a key economic indicator that measures the average economic output per person in a country, expressed in USD.<br>It is calculated by dividing a country's Gross Domestic Product (GDP) by its population | World Development Indicators |
| Ocean Health Index (OHI) | is a metric used to assess the overall health of marine ecosystems, typically on a scale from 0 to 100.<br>This index often incorporates various indicators such as biodiversity, water quality, habitat condition, and the sustainability of human activities like fishing and pollution.<br>The global score is the average of the country scores, weighted by the area of their Exclusive Economic Zone (EEZ). | Oceanhealthindex.org |
| Population Density (people/km²) | is a measure of the number of people living per unit area, typically expressed as persons per square kilometer. | World Development Indicators |

**TABLE 2**
**Variables and source of data**

## RESULTS, DISCUSSION AND POLICY IMPLICATION

The correlation matrix analysis (Figure 3) of desalination drivers in the Mediterranean reveals that there are several significant relationships. For desalination capacity, the strong correlation it has with population density indicates that the most relevant demographic factor driving desalination in the Mediterranean is probably demographic pressure. Additionally, the negative correlation between nominal desalination capacity and the Ocean Health Index indicates that a healthier marine ecosystem reduces reliance on desalination capacity.

The correlation matrix also identifies a moderate positive correlation between renewable energy use and nominal desalination capacity, which suggests that efforts to reduce the energy intensity of desalination are being made. For numerical GDP per capita, correlation with nominal desalination capacity was weak enough not to determine a beneficial relationship, which indicates that economic wealth is not the only important factor in desalination investment.

$CO_2$ emissions had no beneficial correlation with nominal desalination capacity. These findings will contribute to more detailed regression analyses where many different factors will be considered.

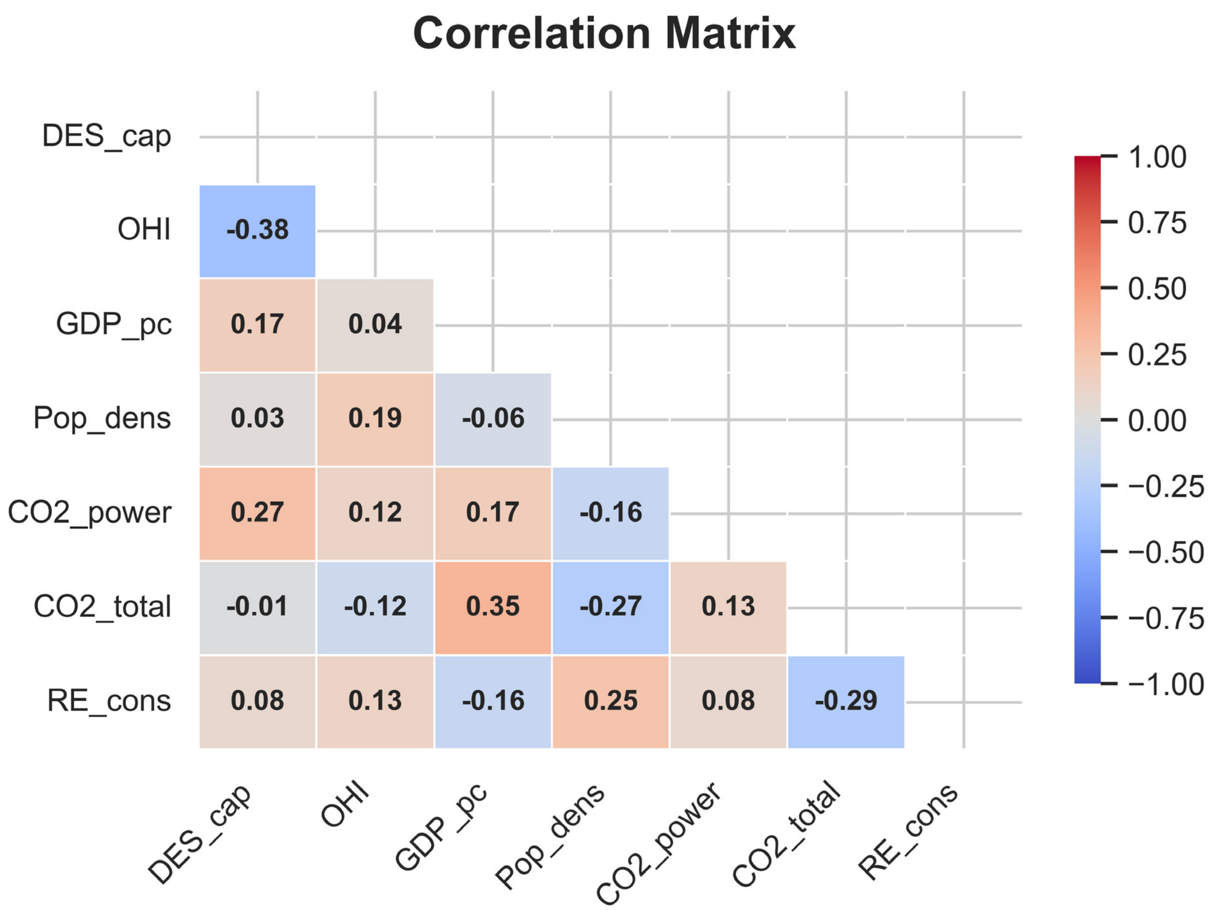



**Figure.3.1** *Correlation Matrix*

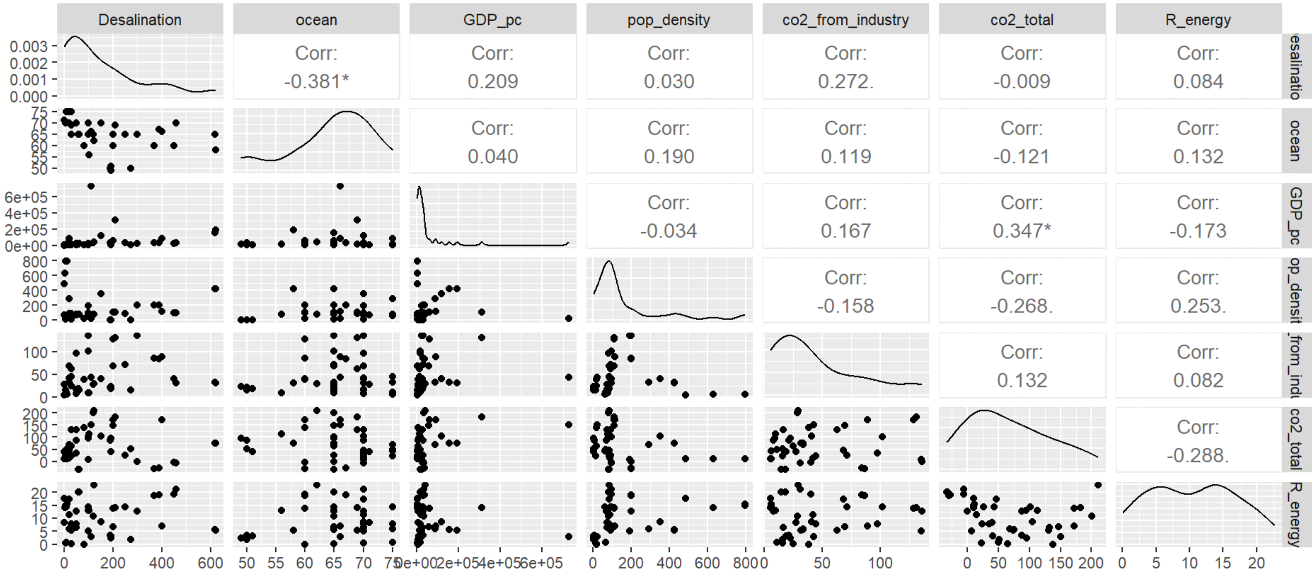



**Figure.3.2** *Source: Authors' calculation*

The data visualization sections in Figure 4, Figure 5 and Figure 6 provides a multi-dimensional exploration of environmental and infrastructural shifts observed in the selected Mediterranean countries between 2000 to estimated 2025, and complex relationships between marine health, $CO_2$ emissions trends, and water security efforts. Exploring $CO_2$ emissions trends identifies impressive variation across regions, as Spain's decline in emissions after 2010 (European Environment Agency, 2022) starkly contrasts Egypt, which appears to be increasing $CO_2$ emissions. The increased emissions in Egypt appear to be tightly correlated to rapid industrialization and population growth (World Bank, 2021). North African countries show relatively stable trends, with Libya appearing to show significant declines due to the impacts of civil war on its industrial activity (UNEP, 2016), while Turkey, facing a similar challenge of reconciling economic development with environmental commitments (OECD, 2021), reports significantly high emissions. As an example of ecological disparities in marine ecosystems, Ocean Health Index data was also included. The report found that Greece and Israel remained relatively high in their OHI scores (70-75) compared to Tunisia, whose OHI score dropped alarmingly ($75 \rightarrow 65$) with substantiated claims of overfishing and coastal degradation (FAO, 2020). Trends emerging from desalination capacity suggest measures adopted in response to growing issues of water scarcity, where Algeria reached peak capacity of (900 $Mm^3/y$) as well as Israel, whose continual investments in increased capacity appear to reflect an intentional strategy for arid climate adaptation (Jones et al., 2018). Egypt has revealed a concurrent decline in OHI score and drop in water desalination capacity, suggesting an increased risk of trade-offs in resource allocation and management. The anticipated stabilization of emissions across most countries suggests some degree of policy efficacy. However, the continued decrease of OHI in Tunisia and Libya suggests fundamental governance issues in the stewardship of marine resources (WWF, 2022).

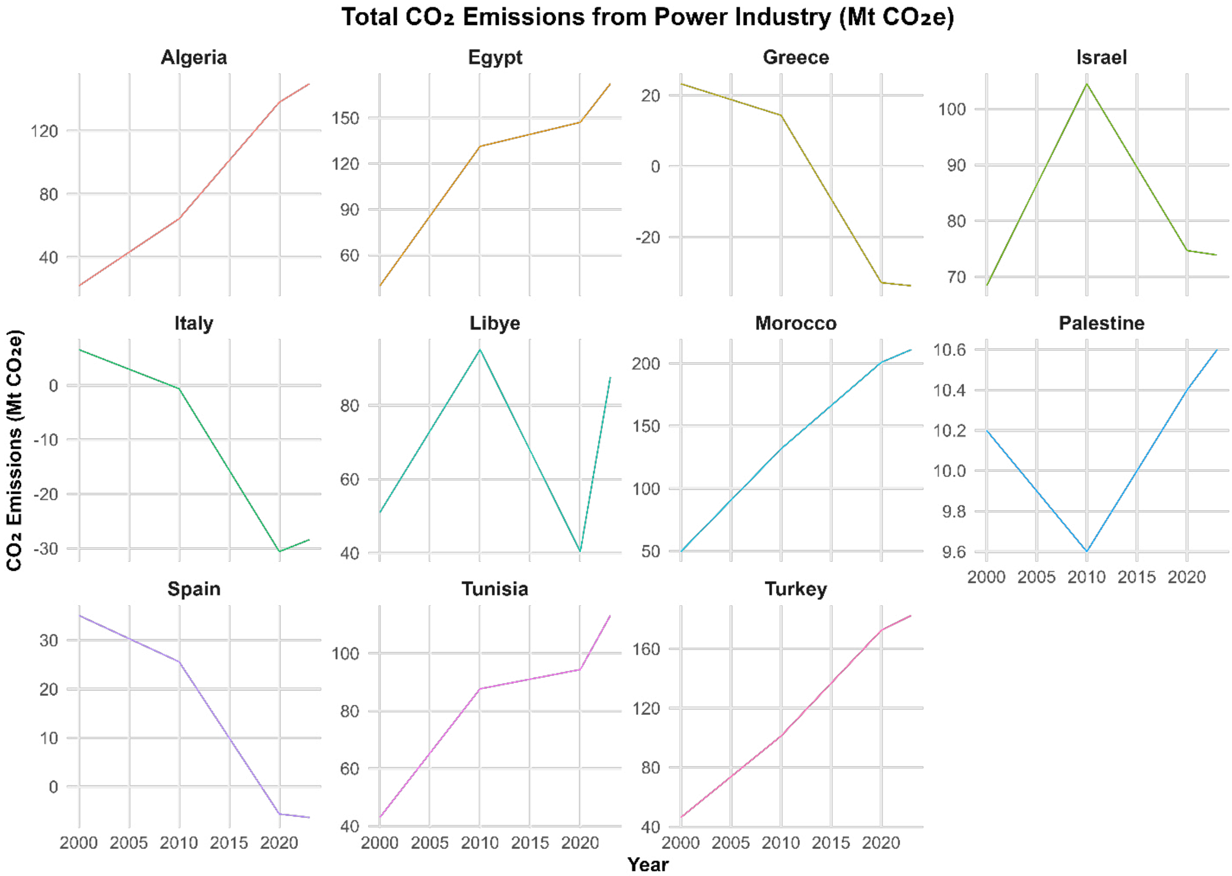



**Figure.4** *Total CO2 Emissions per Country*
*Source: Authors' calculation*

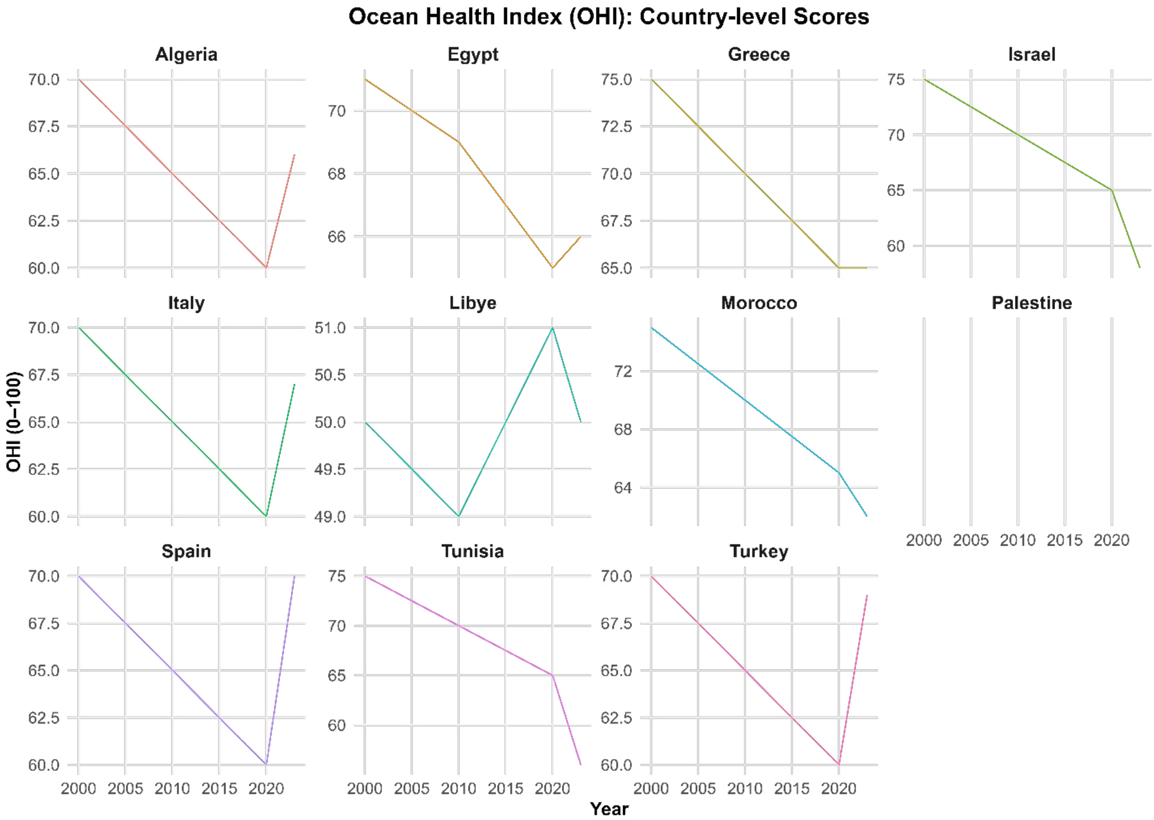



**Figure.5** *Ocean Health Index per Country*
*Source: Authors' calculation*

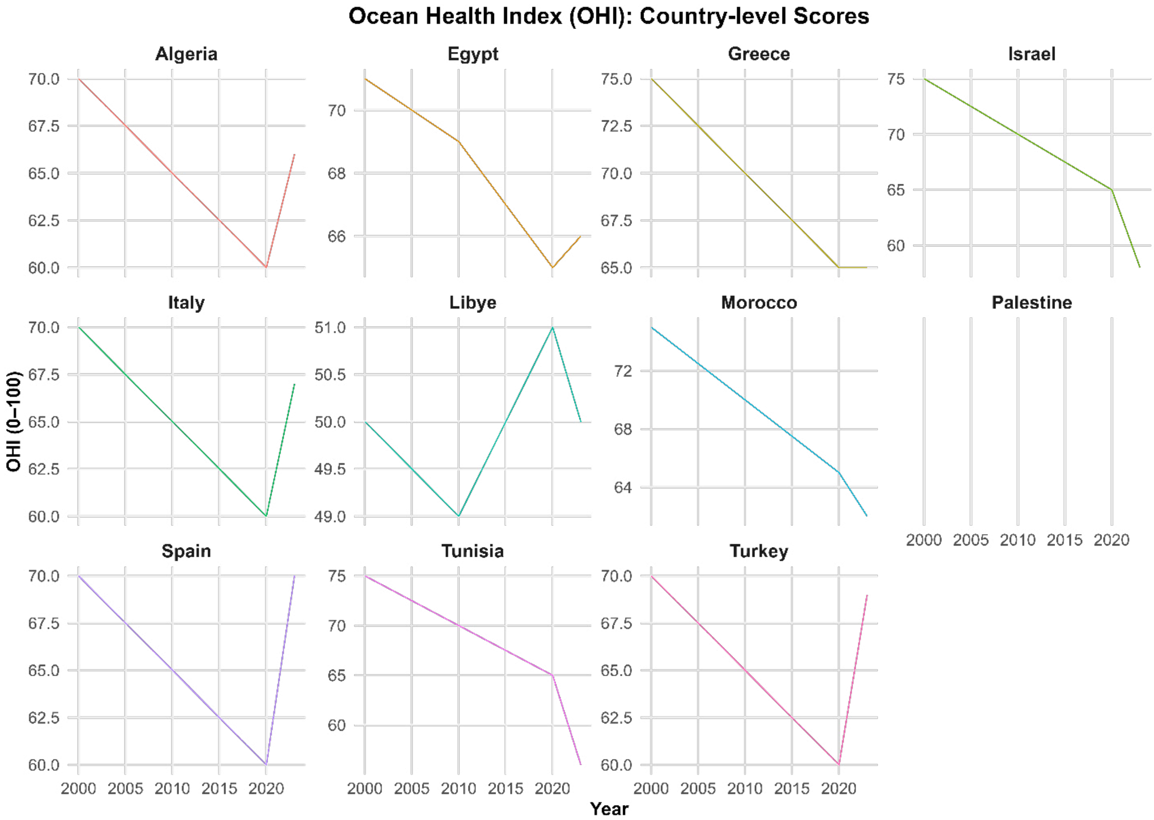



**Figure.6** *Annual Desalination Capacity (Mm3) per Country*
*Source: Authors' calculation*

These linked trends demonstrate the pressing need for integrated policy approaches that can achieve emissions reductions, marine conservation strategies, and improved water and sanitation infrastructure, as called for in a recent sustainability literature review (IPCC, 2023; UNEP/MAP, 2022). The data limitations (for example, Palestine's inconsistent reporting and Morocco's duplicate recording) highlight larger questions of environmental data standards and quality in the region (UNSD, 2022). Ultimately, this emphasizes how stronger monitoring systems and inter-governmental cooperation can help build evidence-oriented environmental policies to reconcile development with the region's environmental vulnerabilities (and opportunities).

The findings (Table 3) from the fixed effects (FE), random effects (RE), and pooled ordinary least squares (OLS) models shed light on the influences that determine desalination capacity across countries.

Model selection followed established specification tests: The F-test (Pooled OLS vs. FE), Breusch-Pagan Lagrange Multiplier test (Pooled OLS vs. RE), and Hausman test (FE vs. RE). The higher explanatory power of the FE model (adjusted $R^2 = 0.661$) compared to RE (0.517) and Pooled OLS (0.554) indicates substantial country-specific heterogeneity in desalination adoption that must be accounted for (Plan Bleu, 2024; Papapetrou et al., 2017).

Population density is a significant predictor ($p<0.01$) in all model specifications, especially in the FE model, where the coefficient is highest (coefficient = 4.991). It seems that as population density increases, countries invest in desalination ,driven by water demand that arises from urbanization in densely populated areas. The ocean health index (OCEAN) has a significant negative relationship ($p<0.01$) in both RE and pooled models (coefficients ≈ -13), suggesting that countries with healthier oceans rely less on desalination, possibly due to more freshwater available from alterna-

| Variables | FE. Model | RE. Model | Pooled. Model |
|---|---|---|---|
| R_Energy | 7.617** (3.341) | 3.604 (3.407) | 4.424 (2.841) |
| CO2_Total | -0.242 (0.359) | -0.326 (0.377) | -0.290 (0.290) |
| GDP_PC | 0.0001 (0.0001) | 0.0002* (0.0001) | 0.0002 (0.0002) |
| Ocean | -2.051 (3.898) | -13.164*** (3.285) | -13.132*** (2.682) |
| POP_Density | 4.991*** (0.769) | 1.374*** (0.333) | 0.969*** (0.179) |
| Constant | | 846.482*** (242.398) | 879.558*** (176.066) |
| Observations | 40 | 40 | 40 |
| $R^2$ | 0.783 | 0.579 | 0.611 |
| Adjusted $R^2$ | 0.661 | 0.517 | 0.554 |
| F Statistic | 18.033*** (df = 5; 25) | 46.805*** | 10.677*** (df = 5; 34) |

**TABLE 2**
**FE, RE and Pooled Regression Models**
*Dependent Variable: Desalination*
**Note: *p<0.1; **p<0.05; ***p<0.01**
*Source: Authors calculation*

tive sources, and/or legislation that mitigates water stress. The adoption of renewable energy (R_ENERGY) has a significant positive relationship (coefficient = 7.617, p<0.05) with desalination capacity in the FE model, but not in the RE and pooled models. This suggests that the link between renewable energy investments and desalination capacity may be particular to selected countries based on policy alignment or technological capabilities.

GDP per capita has a weakly positive effect (coefficient = 0.0002, p<0.1) in the RE model and there is no statistically significant association with $CO_2$ emissions in any specification, which calls into question the idea that higher emission countries are more likely to adopt desalination as a climate change adaptation measure. The FE model has higher explanatory power (adjusted $R^2$= 0.661) than the RE model (adjusted $R^2$ = 0.517) and pooled OLS (adjusted $R^2$ = 0.554), suggesting that 'country level fixed effects' account for unobserved heterogeneity in countries, such as geographic features or long-term policies that drive investment in desalination.

These results highlight the intricate relationship between demographic impacts, environmental conditions, and economic factors in promoting desalination, as well as the necessity to account for 'country fixed effects' in analyses of cross-national infrastructure development. Furthermore, the results carry broader policy implications, particularly in rapidly urbanizing countries that face water scarcity challenges, where integrated planning of desalination infrastructure with coordinated development of renewable energy systems and marine area conservation could result in capacity, efficiency and sustainability benefits for water resources.

While the panel data analysis delivers important preliminary insights, the limited scale of the dataset (11 different countries observed at for income points) inevitably reduces the robustness of the statistical evidence. As a result, these findings should be treated as indicative trends, rather than conclusive outcomes, since small-N studies are especially influenced by outliers or events specific to a particular country. The important aspect, however, across this sample is that the findings converge on a significant policy message that seawater desalination is an urgent and critical response for most of the countries studied, where increasing water scarcity has already begun to impact economic resilience, energy security, and sustainable development. This highlights the role of desalination as not only a technical adaptation, but as a core aspect of national and regional projects for long-term resource management. To boost the current evidence base, future studies would benefit from broadening the time and spatial coverage or supplementing with plant-level data for a stronger and more nuanced basis for policy decisions.

## CONCLUSION

The water constraint situation in the Mediterranean requires a variety of approaches for desalination that balance social, environmental, and economic factors. According to the results, the three main pillars of sustainable desalination are demographic-aware planning, circular brine management, and the integration of renewable energy. While technological developments such as ZLD and RO make efficiency a reality, we also have to consider policy alignment.

Desalination of seawater is not just a technical solution to water scarcity; it is a strategic node in the informal energy-development-environment office. Its legitimacy and sustainability depend on electricity costs, economic capability, and institutional/technical infrastructure. Countries on the south and east sides of the Mediterranean must align their short-term access goals with energy efficiency, cost reform, and climate resilience policies, especially as water and electricity demand is expected to rise due to the increase in population growth and climate change.

At this stage, Mediterranean countries need to implement some strategies to guarantee water resources without compromising ecological resilience by prioritizing sustainability first. They can achieve these goals by :

- Encourage regional collaboration to standardize data reporting and exchange best practices (IPCC, 2023).
- Electricity pricing structures and their impact on operational costs.
- Economic capacity to invest in infrastructure and absorb water tariffs.
- Geopolitical and environmental contexts, including access to the sea, energy reserves, and exposure to climate shocks.
- Brine management solutions such as Zero Liquid Discharge (ZLD) systems, which have shown promise in reducing environmental impacts while remaining economically viable (Panagopoulos, 2022; Chari et al., 2025).

Taking into account the integration of multiple spatial and temporal dimensions implies that policy makers need to start viewing desalination through a systems-based lens rather than a singular cost-benefit analysis lens. The successes of desalination schemes in the Mediterranean region show that an interconnectedness of policy to integrate values and policies from energy, environment, urban development, and water sectors is crucial.

# BALANCING ACCESS AND SUSTAINABILITY: ASSESSING THE ECONOMIC, SOCIAL, AND ENVIRONMENTAL IMPACTS OF WATER DESALINATION IN ALGERIA

AUTHORS : MOURAD KERTOUS, SAMIR MALIKI, OUIEME SOUR

Reservoirs and reverse osmosis equipment © tifonimages


## Abstract

This paper analyzes the economic, environmental, and social impacts of water desalination in Algeria, a key national strategy to address water scarcity exacerbated by population growth and climate change. In alignment with the themes outlined in the call for papers, the study assesses the benefits and challenges of desalination concerning social equity, economic feasibility, and environmental sustainability. The research employs a qualitative analysis of case studies and empirical data on Algeria's desalination infrastructure to formulate sustainable policy recommendations that support water resource conservation and climate resilience.

The paper examines technological advancements and the integration of renewable energy to enhance the sustainability of desalination while addressing key challenges such as high operational costs, energy dependence, and environmental concerns related to brine discharge. Additionally, it investigates public willingness to pay for desalinated water and societal perceptions of its acceptability to uncover trust dynamics. By identifying long-term solutions to reinforce Algeria's water security, optimize resource utilization, and develop climate-adaptive strategies, this study contributes to global discussions on water accessibility and sustainable development in arid and drought-prone regions.


**Keywords :** Water Desalination, Water Scarcity, Desalination Infrastructure, Algeria, Brine Discharge.

## INTRODUCTION

Global population growth, industrial development, irrigation, and improved quality of life have led to an increasing demand for potable water as an essential resource for human survival and well-being. However, access to this resource remains highly unequal worldwide. While some countries benefit from more than 3,000 $m^3$ of water per capita per year, others face water stress, with availability falling below 1,700 $m^3$ per year per capita. In some extreme cases, these numbers can even fall below 500 $m^3$ in per year, resulting in a significant shortage (Fiorenza, G., et al., 2003). Seawater desalination has gradually emerged as a key response to the growing need for freshwater supply, especially with the unavailability of traditional resources i.e., surface and groundwater, in various parts of the world.

Located in the heart of the Mediterranean, Algeria is particularly vulnerable to the effects of climate change. Low precipitation levels and rising temperatures in the region have exacerbated challenges related to water supply. Consequently, Algeria is classified as a state struggling with permanent water scarcity (several literature studies on water management under arid climate conditions have pointed this out, e.g. Kerfouf, A., et al. 2010). These challenges are further compounded by rapid population growth and rapid expansion of industry and higher demands for water for agriculture. In response, Algerian authorities have explored alternative solutions to ensure a sustainable and secure potable water supply. Among these, seawater desalination has emerged as a preferred option, as it is independent of climatic variations.

The most widely adopted technique, reverse osmosis, operates under high pressure, typically between 55 and 80 bar (800–1,200 psi), to filter dissolved salts (Greenlee et al., 2009). This leads to high energy consumption, generally ranging from 3 to 6 kWh per cubic meter of freshwater produced (Ghaffour et al., 2013; Jones et al., 2019). These energy demands translate into operational costs that can vary between $0.50 and $1.50 per cubic meter, depending on plant efficiency, feedwater salinity, and local energy prices (Karagiannis & Soldatos, 2008; Ghaffour et al., 2013). Despite a gradual decline in production costs due to technological advancements and economies of scale, reverse osmosis desalination still requires substantial capital investment, with large-scale plants often costing between $500 million and $1 billion USD (Mezher et al., 2011; World Bank, 2004). This burden is compounded in Algeria by the fact that the majority of energy used in desalination is derived from non-renewable fossil fuels, raising concerns about long-term sustainability and environmental impact (Mezher et al., 2011; El-Kassar et al., 2020).

Desalination plants face a significant environmental challenge beyond financial concerns: the generation and discharge of brine, a highly concentrated by-product at the end of the desalination process. This brine contains a variety of chemicals, including antiscalants and residual cleaning agents, and is often up to twice as salty as seawater, posing a serious threat to marine ecosystems if released untreated. When improperly managed, brine discharges can elevate salinity and temperature levels in coastal waters, affecting marine biodiversity and damaging benthic habitats.
To mitigate these effects, the design and placement of outfall areas, the locations where brine is discharged into the sea are critical. Strategically positioned outfalls with diffuser systems help enhance dilution and dispersion, minimizing localized salinity spikes and ecological harm. Important design considerations include the depth, hydrodynamic conditions, and proximity to sensitive coastal zones, as poor placement can exacerbate environmental degradation (Lattemann & Höpner, 2008; Jones et al., 2019).

Poor disposal practices can greatly damage marine plants and animals, alter ecological systems, and affect other water quality. Brine discharges have a direct impact on fish populations, coral reefs and aquatic diversity so it is crucial to manage brine discharges properly so that desalination practices can be sustained over a long time. Some recent studies posit that there is a need to optimize brine management practices to limit the hazards caused by their volume (Isari et al., 2020).

In this context, Algeria has developed an ambitious plan to increase its desalination capacity, in light of a growing water scarcity and to diversify sources of freshwater (Kerfouf et al., 2010). Although desalination represents a crucial pathway forward for addressing freshwater shortages, it poses profound challenges for sustainability. The basic challenge is in finding an equilibrium between the economic, social and environmental trade-offs of the technology and the effective management of the resource (water) in the long term.

This research aims to evaluate the socio-economic as well as environmental impact caused by desalinating seawater in Algeria. More specifically, we want to assess if and how this technology can be used sustainably, both in terms of scale and efficiency. This includes examining measurable indicators such as the number and geographic distribution of desalination plants, the volume of desalinated water produced, the percentage of the population served, and the share of desalinated water in the total national supply. We will also explore the social implications, particularly regarding access to potable water for vulnerable and underserved populations, and evaluate the environmental challenges, with a specific focus on brine discharge management and marine ecosystem impacts. The central research axis driving this study is:

### *Socio-economic and environmental impacts of seawater desalination in Algeria*

To address this issue, our research is structured into several sections. We begin with a methodology section, which outlines the modeling framework used to project future water demand, desalination infrastructure needs, and brine discharge volumes, as well as the design of a household survey assessing social acceptability. This is followed by a literature review that examines global and national insights into desalination technologies, environmental impacts, and economic considerations. Next, we analyze water availability in Algeria, offering context for the country's strategic shift toward desalination. We then examine water management policies, distinguishing between supply-side and demand-side approaches. This is followed by an overview of desalination in Algeria, detailing the national program, technologies employed, and cost structure. The subsequent sections present projections to 2100 and assess public perception based on field survey data. Finally, the paper concludes with key challenges and policy recommendations to guide sustainable water management.

## RESEARCH METHODOLOGY

This research adopts a mixed-methods approach, integrating both qualitative and quantitative analyses to assess the economic, environmental, and social impacts of water desalination in Algeria. The methodological framework includes three core components: (1) literature review and institutional data collection, (2) prospective modeling for forecasting water demand and environmental implications, and (3) a household survey to evaluate public perception and social acceptability.

### *Literature and Data Collection*

The first stage involved an extensive literature review, drawing from peer-reviewed academic publications, government reports, and international databases (e.g., World Bank, UNEP, GWI, Plan Bleu, and FAO). This review provided contextual understanding and enabled the identification of key variables related to desalination costs, energy use, brine discharge, and social equity concerns.
Empirical data were collected on the following aspects:

- The number and capacity of existing desalination plants in Algeria
- Operational and capital expenditure (OPEX and CAPEX)
- Energy consumption rates by desalination technology
- National statistics on water availability and population growth (ONS, 2022)
- Forecast scenarios from international references for comparative analysis

### *Modeling Water Demand and Environmental Impact (2024–2100)*

To project Algeria's future water needs and related environmental pressures, a prospective model was developed based on exponential population growth and a fixed national water availability scenario (12 billion m³/year). The model included the following components:

- *Population Projections were estimated using an exponential growth formula:*

$$P_t = P_0(1+r)^n$$

where: $P_0$ = 46.5 million (2024), r = 2% and n is the number of years.

- *Water Availability Per Capita was calculated by:*

$$D_t = \frac{12\ billion\ m^3}{P_t}$$

- *Water Deficit was calculated using:*

$$B_t = P_t \times 500\ m^3 \quad \text{and} \quad Water\ Deficit = B_t - 12\ Billion\ m^3$$

- *Desalination Infrastructure Needs: The number of desalination plants needed was estimated assuming each plant produces 200,000 m³/day:*

$$Number\ of\ Pants = \frac{Deficits}{200{,}000 \times 365}$$

- *Brine Discharge volumes were estimated by assuming a simplified discharge ratio of 1.5 liters of brine per 1 liter of freshwater produced:*

$$Discharges_t = Production \times 1{,}5$$

*While this assumption is a useful simplification, brine-to-water ratios in practice vary depending on seasonal demand and technology used.*

*The forecasts were generated for three key reference years: 2025, 2050, and 2100. A combined table of projected population, per capita water availability, total water deficit, number of required desalination plants, and expected brine discharge is included to consolidate the modeling results.*

### *Household Survey Design and Analysis*

To evaluate the social acceptability and public perception of desalinated water, a structured household survey was conducted in Western Algeria, particularly in Tlemcen province. The survey targeted 200 randomly selected households, representing diverse socio-economic groups.

The questionnaire consisted of 30 questions that were grouped into five major thematic areas. These included household habits regarding water consumption, perceptions of the quality of desalinated water, and respondents' willingness to pay for improved service. It also explored the degree of confidence in desalination technologies and the level of support for public desalination policies. This thematic structure enabled a comprehensive understanding of both behavioral and attitudinal dimensions related to water use and acceptance of desalination.

Responses were analyzed using Sphinx software. These survey insights were then triangulated with the technical and economic analysis to produce a comprehensive understanding of desalination's feasibility and societal reception in Algeria.

## LITERATURE REVIEW

In areas like Algeria where freshwater supplies are scarce, seawater desalination has emerged as a crucial remedy for water stress. Two primary technologies are widely employed: membrane processes, such as reverse osmosis (RO), which operate on electrical energy, and thermal procedures, including Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED), which require thermal energy from sources like fossil fuels, solar, or nuclear power (Al-Karaghouli & Kazmerski, 2013). In Algeria, reverse osmosis dominates, accounting for approximately 85–90% of total desalination capacity, while thermal technologies (mostly MSF and MED) make up the remaining 10–15%, primarily in older or government-run installations (GWI, 2023; UNEP, 2021).

In recent years, the country has started exploring more sustainable options by integrating renewable energy sources, such as solar thermal, photovoltaic, and wind, into desalination operations to reduce reliance on fossil fuels and mitigate environmental impacts.

However, desalination presents significant environmental challenges. The discharge of concentrated brine and the chemicals used in the pre-treatment of installations can severely impact marine ecosystems. Al-Karaghouli, A., and Kazmerski, L. L. (2013) highlight that the salinity of discharges from reverse osmosis plants is approximately twice that of seawater, while discharges from thermal processes have a salinity about 15% higher, with temperatures 5 to 10°C above the marine environment. This increase in temperature reduces dissolved oxygen concentration, which in turn affects aquatic biodiversity. In addition to these thermal variations, salinity gradient increases disturb seawater stratification and create a brine plume that is denser than the surrounding seawater. As this plume sinks towards the benthic zone, it affects exposed marine species by altering the local environment. Elimelech, M., and Phillip, W. A. (2011) also emphasized the environmental consequences of thermoelectric processes, which generate significant greenhouse gas emissions. According to their estimates, modern reverse osmosis facilities consume between 3 and 4 kWh/m$^3$ of produced drinkable water, resulting in emissions of 1.4 to 1.8 kg of $CO_2$ per m$^3$. Additionally, the use of chemicals for membrane pre-treatment and cleaning exacerbates marine pollution.

From an economic perspective, the cost of desalination depends on several factors, including initial investment, type of energy used, water quality, and labor costs. Lasseur, E., et al., (2009), in his study on desalination in the Arabian Peninsula, demonstrates that the choice of technology is heavily influenced by a country's energy resources. For example, Gulf countries favor MSF processes (Multi-Stage Flash distillation) due to their abundant fossil fuel resources, despite their high energy costs. Conversely, reverse osmosis is more energy-efficient but requires a higher initial investment. The analysis by Zhou, Y. and Tol, R, S., (2005) indicates a significant reduction in desalination costs over the decades. The unit cost of the MSF process dropped from \$9/m$^3$ in 1960 to \$1/m$^3$ in 2001, while for reverse osmosis, it declined from \$5/m$^3$ in 1970 to \$1/m$^3$ in 2001. The integration of renewable energies into desalination appears to be a promising solution for reducing the carbon footprint of this technology. Zhou, X., et al. (2018) studied the costs of solar desalination and concluded that this method remains relatively expensive due to the high price of solar collectors. However, they anticipate that future technological developments and lower solar panel production prices will make this option more competitive.

Water and energy subsidies are critical to the sustainable future of desalination. In the paper «Water Subsidies, Desalination and Sustainable Resource Management: Lessons from Algeria,» Maliki S.B et al. (2024) assessed how subsidy policies apply to the development of desalination. They included recent regulations and trends in energy consumption in Algeria as a part of their analysis and were able to determine the relevance of energy subsidies for desalination, especially in a country where natural gas production is an essential component of its economy.

Their results suggest that if water and energy subsidies were reduced, desalination costs could potentially be out of reach for a considerable share of the population, representing a significant governance problem. They conclude with the important message that desalination can provide access to potable water; however, any associated cost increases from the costs would lead to serious social implications, primarily affecting the most vulnerable households.

Nonetheless, desalination provides a necessary source of potable water in Algeria, where as many as nearly 15 million people either currently depend on it or will shortly (World Bank, 2021). This technology not only alleviates tensions related to water shortages but also reduces waterborne diseases through stricter water quality control (Lattemann & Höpner, 2008). It also helps curb internal migrations driven by drought, which particularly affect rural areas (Mezher et al., 2011).

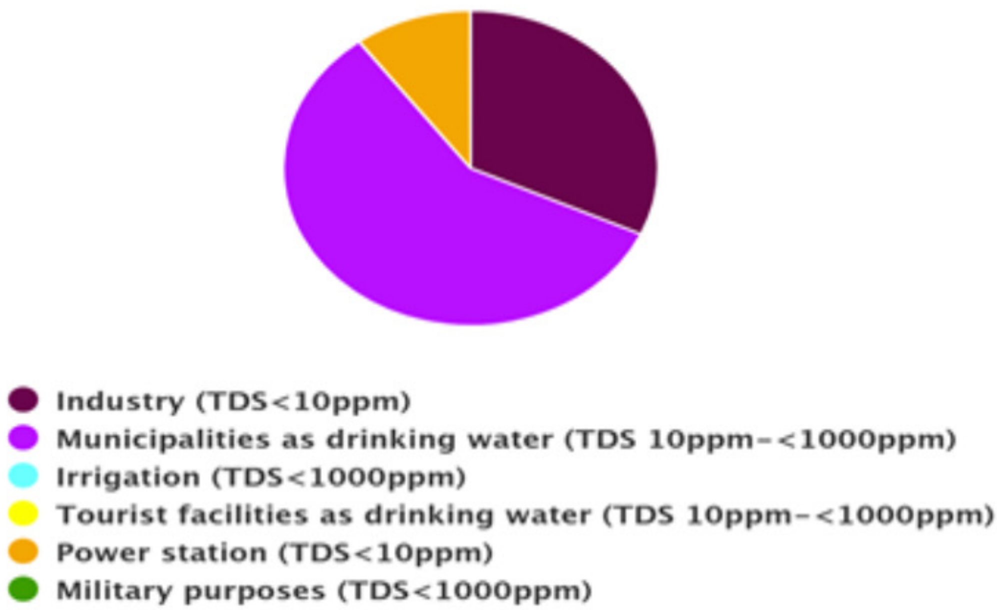



**Figure.1** *Distribution of Desalinated Water by Sector in Algeria*
*Source: Desaldata, adapted from Plan Bleu Observatory (2023)*

Furthermore, desalination stimulates multiple economic sectors, including agriculture, industry, and tourism. According to Desaldata (2023), the largest share of desalinated water in Algeria is allocated to municipalities as drinking water (around 60%), followed by industry (approximately 30%) and power stations (about 10%). This distribution underscores the role of desalination in supporting both human consumption and industrial productivity. Water-intensive sectors such as petrochemicals and agri-food benefit from a stable supply, strengthening their competitiveness (Karagiannis & Soldatos, 2008). By ensuring reliable water access, desalination also fosters foreign investments and tourism development (World Bank, 2021). A notable example is the Fouka complex, which has created hundreds of jobs in the construction and operation of the plant (Ministry of Water Resources, 2022).

From an environmental perspective, although desalination poses challenges related to brine discharge and energy consumption, it helps reduce pressure on groundwater reserves and dams, which are often overexploited. This technology thus contributes to the preservation of wetlands and aquatic ecosystems, which play a key role in water regulation and biodiversity (Lattemann, S., & Höpner, T., 2008). Finally, desalination is perceived as a climate adaptation solution, ensuring a stable and climate-independent water source, a crucial issue for Algeria amid increasing drought periods (World Bank, 2021).

## WATER AVAILABILITY IN ALGERIA

The water availability in Algeria exists within restricted boundaries due to the uneven geographical distribution of water resources across its territory. Surveys position Algeria as the 16th most water-scarce nation globally. The country is divided into five main hydrographic basins: Oranie-Chott Chergui, Cheliff-Zahrez, Algerois-Hodna-Soummam, Constantinois-Seybousse-Mellegue, and the Sahara basin, which include a total of 19 watersheds aligned mostly north to south (see Figure 2).

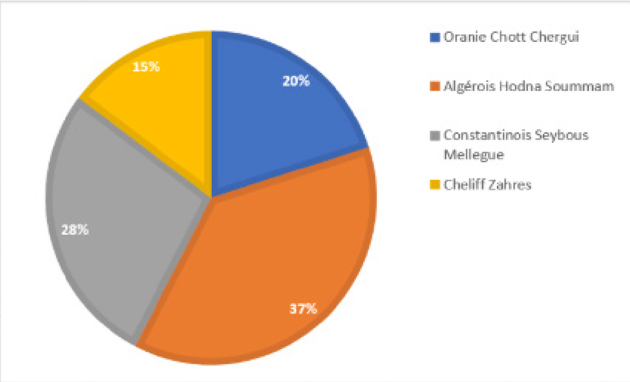
These basins differ significantly in terms of precipitation, water infrastructure, and population density. The Oranie-Chott Chergui and Cheliff-Zahrez basins, located in the semi-arid west and center, are among the most vulnerable due to low rainfall and high demand. The Algerois-Hodna-Soummam basin, covering the populous central coastal region including Algiers, faces severe pressure from urban consumption and pollution. The Constantinois-Seybousse-Mellegue basin in the east is relatively better supplied, though still under seasonal stress. The Sahara basin, covering over 80% of Algeria's surface, holds vast fossil aquifers but has extremely limited renewable water resources.

Since independence, Algeria's water availability per capita has steadily declined from 1,500 m³/year in 1962 to just 397 m³ today and is projected to reach only 220 m³ by 2050, well below the 500 m³ threshold for absolute water scarcity.


**Figure.2** *Representation of the Five Hydrographic Basins in Algeria*
*Source: Algerian Ministry of Water Resources*

Algeria's total renewable water availability is estimated at around 18 billion m³ per year, far below the Mediterranean average. According to FAO data, the per capita renewable water availability in Algeria is below 500 m³/year, while countries like France or Italy exceed 2,000 m³/year, placing Algeria in the extreme water stress category compared to many Mediterranean nations.

These limited resources are also unevenly distributed across regions. The northern part, which represents only 7% of the national territory, receives around 12.5 billion m³/year, with 10 billion m³ coming from surface water and 2.5 billion m³ from renewable groundwater. In contrast, the Saharan regions, including the High Plateaus and Saharan basins, account for about 5.5 billion m³/year, of which 0.5 billion m³ comes from surface water and 5 billion m³ from fossil aquifers.
These fossil aquifers are a major but non-renewable source, posing critical challenges for sustainable water management. To better understand the spatial disparity of water resources, a map-based representation could be added to highlight the distribution of surface and groundwater resources across the five hydrographic basins, complementing the existing pie charts and enabling a clearer geographic understanding of regional water potential and stress.



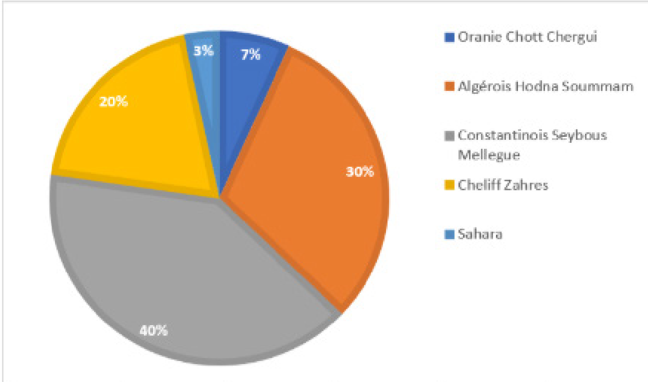




**Figure.3** *Distribution of Surface and Groundwater Resources Across different Hydrographic Basins*
*Source: Algerian Ministry of Water Resources*

The water resources in the nation follow a major uneven pattern of distribution. Eastern Algerian basins represented by Constantinois Seybous Mellegue, along with Algérois Hodna Soummam, control about 70% of the national surface water resources. Other parts of Algeria remain restricted from accessing their fundamental water resource supply. Groundwater resources of the Algérois Hodna Soummam basin exceed those of the western Chellif Zahres basin by more than double the amounts.

These inequalities in water resource distribution, combined with a continuous decline in water availability, necessitate rigorous and sustainable management. The effective solution to Algeria's growing water scarcity problems will require alternative actions, including seawater desalination combined with optimized irrigation distribution and conscious water usage promotion among citizens.

## WATER MANAGEMENT POLICY IN ALGERIA

Algeria's water policy is structured around two main strategic pillars: the first focuses on hydraulic infrastructure development, while the second emphasizes resource optimization and conservation. These approaches align with Supply-Side Management and Demand-Side Management, respectively, as mentioned in Table 1.

| Aspect | Supply-Side Management | Demand-Side Management |
|---|---|---|
| **Objective** | Increase water availability through infrastructure development | Optimize water use and reduce waste |
| **Strategy** | Building dams, reservoirs, desalination plants, and wastewater treatment | Awareness programs, tariff reforms, rationing, water meter installation |
| **Governance Measures** | Large financial investments, public-private partnerships, national water programs | Public education, progressive tariffs, monitoring consumption |
| **Main Programs** | Regional water transfer programs, desalination, wastewater recycling | Water conservation awareness, educational campaigns, rationing |
| **Investment Focus** | Hydraulic infrastructure, desalination plants, boreholes, reservoirs | Consumer behavior change, cost recovery |
| **Challenges** | Financial dependency, regional disparities in access | Public behavior change, intermittent distribution |

**TABLE 1**
**Supply-Side Management and Demand-Side Management**
*Source: Author's elaboration*

### *Supply-Side Management*

Public authorities introduced a supply-driven policy to address issues such as population growth, rising living standards, and decreasing rainfall, particularly after the 2001 drought. This approach involved substantial financial investment in hydraulic infrastructure, including new dams, hillside reservoirs, boreholes, and desalination plants. Water transfer programs at the regional level aim to equalize access across different areas, focusing on agricultural zones as part of the national food security plan.

### ***Investments in the Water Sector***

The government has made significant financial investments in hydraulic facilities, allocating 2,297 billion Algerian dinars (about 23 billion euros) between 1999 and 2009. Investments continued at similar levels in the subsequent decade, resulting in the modernization of dams, reservoirs, desalination plants, and wastewater treatment stations.

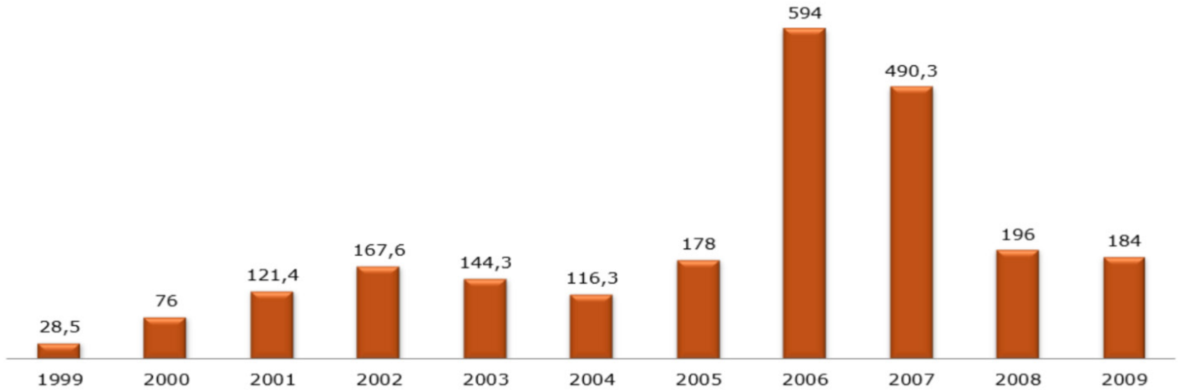



**Figure.4** *Annual Investments in Algeria's Water Sector (1999 - 2009)*
*Source: Algerian Ministry of Water Resources*

### *Demand-Side Management*

The Water Law of 2005 emphasizes the rational management of water resources and aims to reduce waste. Several measures have been put in place to optimize consumption and encourage responsible use:

- Awareness Programs: The Hydraulic Basin Agencies (Agences de Bassins Hydrauliques - ABH) have been promoting water conservation through education, including a «Water Class» module introduced in school curricula and media campaigns.
- Tariff Reforms: A progressive pricing system was introduced to align water costs with actual consumption. This system aimed to improve cost recovery and reduce waste.
- Water Rationing: In areas facing chronic scarcity, intermittent water distribution has been used as a mechanism to regulate demand and ensure minimum access.
- Water Meter Installation: The widespread installation of water meters allows for better tracking of household and industrial consumption, leading to more accurate billing and reducing unmonitored losses.

## STATUS OF DESALINATION IN ALGERIA

### *Desalination Program in Algeria*

Desalination projects in Algeria date back to the early 1980s, with the establishment of the first desalination units along the coast (Skikda and Arzew) to meet the water needs of industrial zones. However, it was not until 2003 that favorable conditions allowed for the launch of several large-scale projects under the supervision of the Ministry of Water Resources (MWR).

The Algerian desalination sector contains 25 seawater desalination plants (SWDPs), yet the country plans to construct 11 new plants under its complementary program launched in 2022. According to Lahcene Bada CEO of Algerian Energy Company, Algerian desalination facilities have secured the leading position among all African seawater desalination establishments. Algerian President Abdelmadjid Tebboune reaffirmed in December 2024 that the new desalination facilities would begin operation in February 2025 to ensure a reliable drinking water supply.

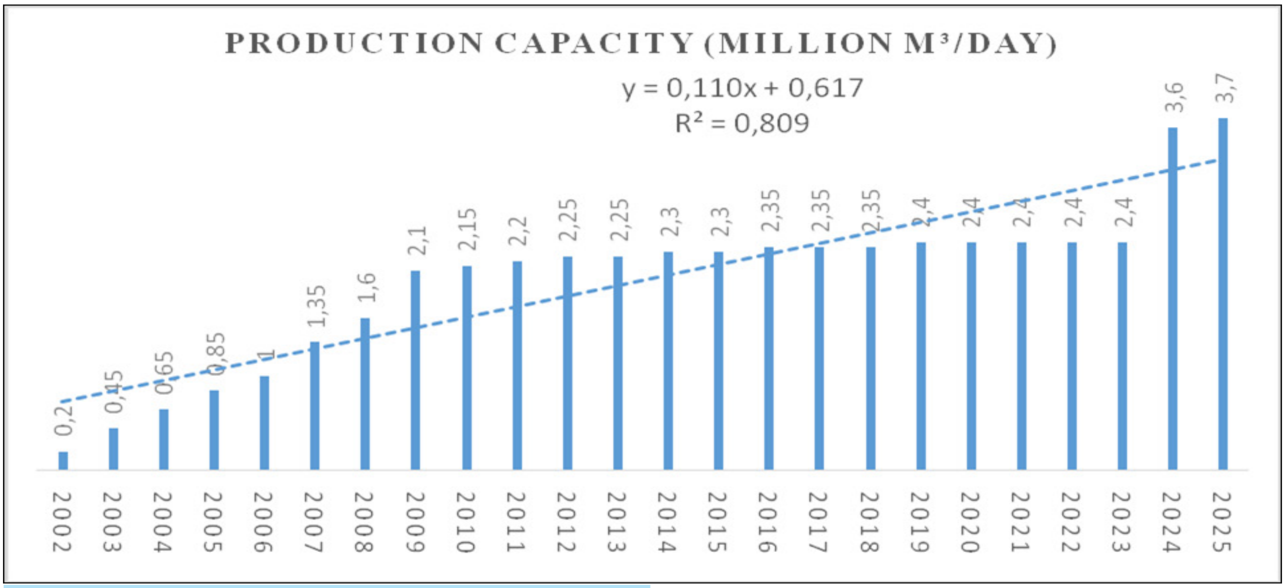



**Figure.5** *Evolution of Water Desalination Production Capacity (1995-2022)*
*Source: Author's computation*

The desalinated water output of Algeria reaches 2.1 million m³ daily through its 14 operational desalination plants installed along the coastal regions. The national production capacity of desalinated water is projected to reach 3.6 million m³ per day after every project under the complementary presidential program has been constructed. Each new plant built under this program will have a daily capacity of 300,000 m³. The predicted total addition brought by water supply will generate 1.5 million m³ daily.

The country now deeply recognizes water resources as vital components for maintaining stability together with both security and socio-economic development. The substantial investments in desalination infrastructure help Algeria both eliminate climate-dependent water supply risks and establish full control over its water resources. The nation's autonomy depends heavily on this water independence factor.

The government has allocated large financial resources to the desalination industry because of reservoir water depletion which resulted in complete dry-ups of facilities like Bakhadda reservoir in Tiaret during the summer of 2024.

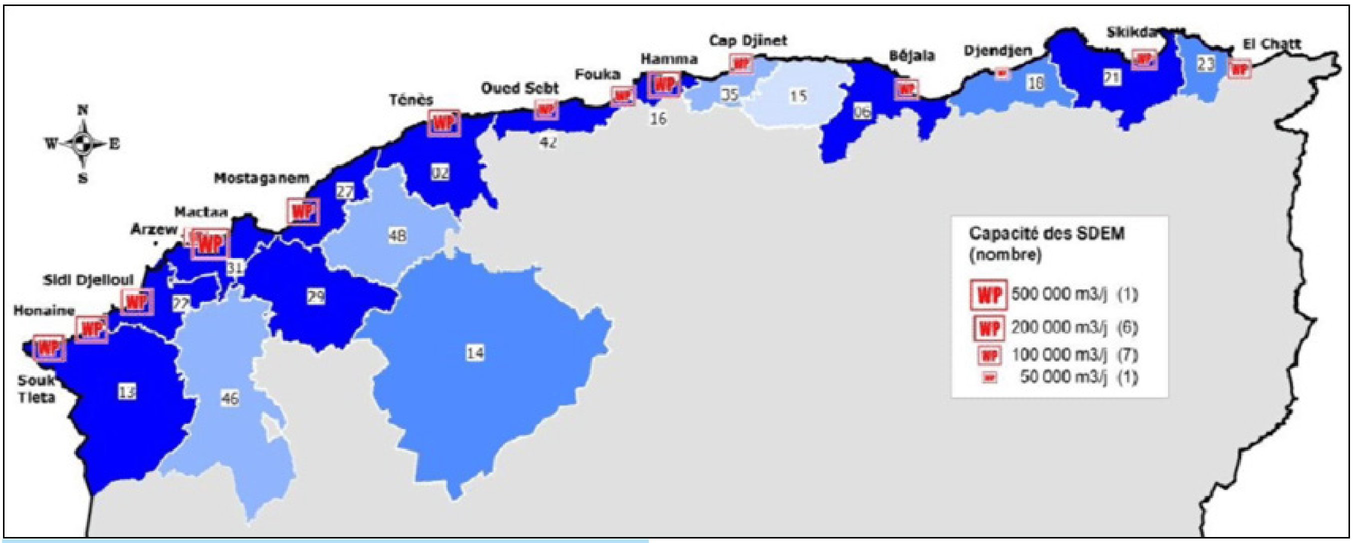



**Figure.6** *Spatial Distribution of the Main Desalination Plants in Algeria*
*Source: https://algeriepart.com/wp*

## *Development of Desalination Technologies*

Desalination, particularly through reverse osmosis (RO), is essential for Algeria's water supply, especially in drought-prone regions. RO technology, which uses high pressure to push seawater through semi-permeable membranes, is favored for its energy efficiency and cost-effectiveness, despite its high energy demands. It now accounts for 80% of global desalination facilities. While thermal distillation remains an option, RO is more resource-efficient and economically viable.

Ongoing research is integrating renewable energy sources, like solar and wind power, to reduce reliance on fossil fuels and minimize environmental impacts. The advancement of RO membranes and energy recovery systems has made desalination more accessible and affordable. However, ecological concerns, particularly brine disposal, remain a challenge, necessitating sustainable management practice.

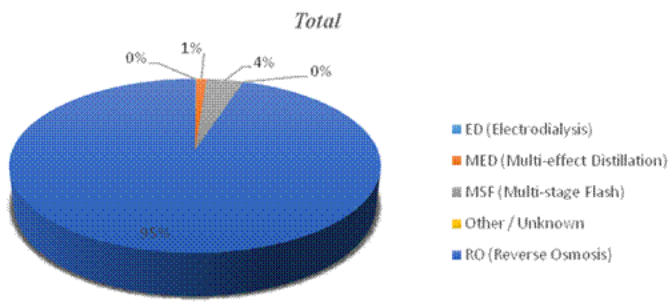



**Figure.7** *Distribution of Desalination Technologies in Algeria*
*Source: Authors' calculations based on Plan Bleu Observatory data (DesalData Database, GWI group)*

## *The Costs of Water Desalination in Algeria*

Water desalination initiatives throughout Algeria maintain a critical position because they solve water shortages together with their expanding drinking water requirements. The data released by Plan Bleu (2024) shows a substantial rise in desalination capital expenditures (CAPEX) throughout Algeria due to an anticipated 96.31% yearly increase from 2018 through 2027. The government maintains its firm dedication to developing robust desalination facilities as indicated by current trends.

However, operating expenditures (OPEX) remain a major challenge due to high energy consumption and maintenance costs. Reports indicate that OPEX reaches \$134/m³ for plants utilizing seawater reverse osmosis (SWRO) and \$145/m³ for those using multi-effect distillation (MED). The following graph illustrates this evolution in investments and operating costs, highlighting the scale of resources allocated to support desalination in Algeria.

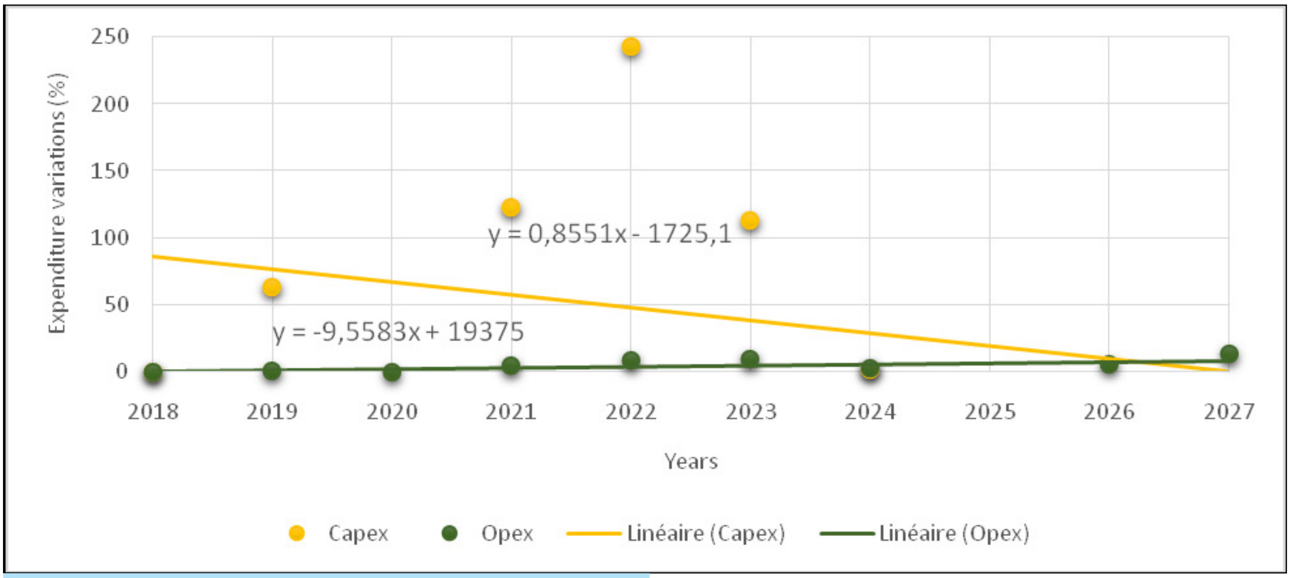



**Figure.8** *Expenditure Variation in CAPEX and OPEX in Algerian Desalination Plants*
*Source: Authors' calculations based on Plan Bleu Observatory data (DesalData Database, GWI group)*

Regarding the cost of desalinated water, estimates for Algeria vary depending on the technology used:

- Seawater Reverse Osmosis (SWRO): \$0.84/m³
- Multi-Effect Distillation (MED): \$1.15/m³

These costs remain relatively competitive compared to other Mediterranean countries. For instance, in Spain, the cost of SWRO desalinated water ranges from \$0.90 to \$1.50/m³, depending on plant size and energy pricing. In Tunisia, due to smaller-scale operations and less energy-efficient infrastructure, SWRO costs are typically between \$1.05 and \$1.30/m³ (Plan Bleu, 2022; GWI, 2023).

Algeria's capital expenditure (CAPEX) for desalination plants is estimated at \$1,000 to \$1,200 per m³/day of installed capacity, while operating expenditure (OPEX) reaches approximately \$134/m³ for SWRO and \$145/m³ for MED. In comparison, Spain's CAPEX for modern SWRO facilities averages around \$1,200/m³/day, and OPEX ranges from \$0.50 to \$0.70/m³, depending on the use of energy recovery technologies and plant efficiency.

To enhance long-term sustainability, Algeria needs to modernize its infrastructure and integrate renewable energy sources to reduce fossil fuel dependency and lower production costs. Between 2000 and 2020, the average cost of desalination in Algeria declined by approximately \$0.10/m³ every five years, reflecting progress in technology, energy strategy, and public policy.

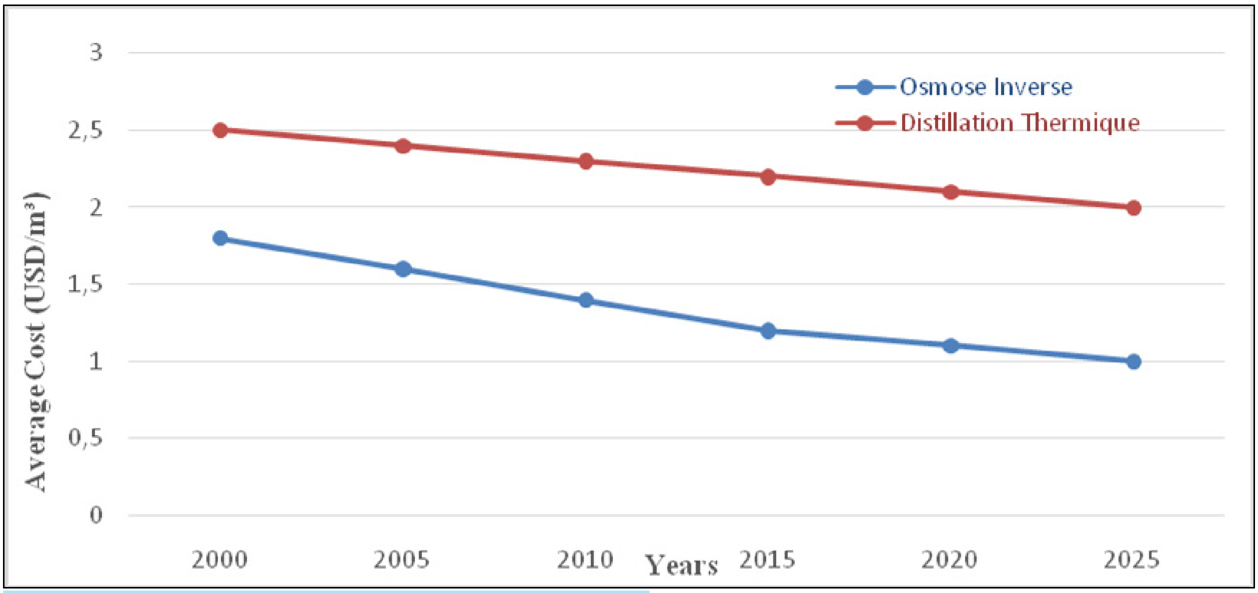



**Figure.9** *Evolution of Desalination Costs (2000 - 2025)*
*Source: Authors' calculations based on Plan Bleu data*

It is observed that CAPEX tends to decrease with technological innovation, whereas OPEX remains a major challenge. Thermal processes (distillation) are particularly affected, with operational costs decreasing slightly from \$2.5/m³ in 2000 to \$2.0/m³ in 2025, yet remaining higher than SWRO costs.

Several interrelated factors influence desalination costs:

- Salinity and quality of feedwater
- Plant capacity / technology / maintenance
- Energy use and labor costs
- Regulatory, political, and environmental constraints

Given the high energy costs associated with desalination, Algeria is exploring sustainable alternatives. The integration of renewable energy appears to be a promising solution for reducing reliance on fossil fuels and minimizing long-term costs. Studies, such as those by Zhang, Y et al. (2018), suggest that solar-powered desalination could become more competitive in the coming years, despite high initial investment costs related to solar panels and energy storage infrastructure.

| Water Cost (USD/m³) | |
|---|---|
| Average | 0.739925 |
| Median | 0.735 |
| Standard Deviation | 0.097576574 |
| Range | 0.34 |
| Minimum | 0.56 |
| Maximum | 0.9 |
| Number of Samples | 8 |

**TABLE 2**
**Desalination Costs Based on a Sample of Eight Desalination Plants**
*Source: Authors' calculations based on Plan Bleu data*

The expansion of desalination capacity in Algeria not only responds to the growing water demand but also benefits from gradual cost reductions driven by technological advancements (Ghaffour, N., et al., 2013). These innovations make desalinated water more competitive compared to other water sources. However, the high energy consumption of desalination plants remains a significant obstacle, directly impacting the final cost of water.

The adoption of sustainable energy sources will be essential to ensuring the economic and environmental viability of desalination in Algeria in the long term.

## PROJECTIONS OF WATER DEMAND AND WASTE FOR 2100 IN ALGERIA

This section presents the projected outcomes derived from the modeling framework detailed in the methodology. The projections illustrate the increasing pressure on Algeria's water resources due to population growth and highlight the scale of investment required in desalination infrastructure and brine management by 2100.

### *Population Growth, Decline in Water Availability and Water Deficit*

According to the exponential growth model, Algeria's population is projected to reach 68 million by 2050 and 143 million by 2100, a threefold increase from the current population. Given a constant national freshwater availability of 12 billion m³/year, this population growth will lead to a sharp decline in water availability per capita:

| Year | Projected Population | Water Availability (m³/capita/year) |
|---|---|---|
| **Average** | 49 million | 260 |
| **Median** | 68 million | 176 |
| **Standard Deviation** | 143 million | 83 |

**TABLE 3**
**Projected Population and Water Availability in Algeria (2025-2100)**
*Source: Author's elaboration*

This trend places Algeria well below the 500 m³/year threshold for absolute water scarcity, as defined by the World Health Organization.

To maintain a minimum of 500 m³ per person annually, the estimated water demand will significantly exceed the fixed supply. The resulting deficits are:

| Year | Projected Water Deficit (Billion m³) |
|---|---|
| **2025** | 11 |
| **2050** | 22 |
| **2100** | 59 |

**TABLE 4**
**Projected Water Deficit in Algeria (2025-2100)**
*Source: Author's elaboration*

These Tables underline a widening gap between supply and demand, which calls for urgent water management interventions.

### *Desalination Infrastructure Requirements and Brine Discharge Projections*

To bridge the projected water deficits, Algeria would require substantial increases in desalination capacity. Based on a standard daily output of 200,000 m³ per plant, the following additional desalination plants would be required:

| Year | Projected Water Deficit (Billion m³) |
|---|---|
| **2025** | - 52 |
| **2050** | - 82 |
| **2100** | - 185 |

**TABLE 5**
**Projected Plants Needed in Algeria (2025-2100)**
*Source: Author's elaboration*

This implies a nearly fourfold expansion in infrastructure over the next 75 years, particularly along the coastal regions where seawater access is feasible.
As desalination output rises, so will the volume of

brine discharged into the marine environment. Assuming an average brine-to-freshwater ratio of 1.5, the expected annual brine volumes are as follows:

| Year | Brine Discharge (Billion m³/year) |
|---|---|
| 2025 | 17 |
| 2050 | 33 |
| 2100 | 90 |

**TABLE 6**
**Projected Brine Discharge in Algeria (2025-2100)**
*Source: Author's elaboration*

The ecological implications of these discharges will depend on brine management practices and the implementation of mitigation technologies.

These projections reinforce the urgency of sustainable planning. Algeria faces an intensifying water crisis that cannot be addressed solely through traditional supply-side solutions. Expanding desalination capacity, optimizing water use, and integrating renewable energy will be essential for long-term water security. In parallel, environmental policies must be strengthened to prevent the degradation of marine ecosystems due to brine discharge.

## ASSESSMENT OF HOUSEHOLDS' SOCIAL ACCEPTABILITY IN ALGERIA

To complement the technical and environmental analysis, a field survey was conducted to assess public perception and social acceptability of seawater desalination in Algeria. The survey targeted 200 households in the Tlemcen region, chosen for its increasing reliance on desalinated water. This section presents the main results of the survey and offers insights into users' acceptance, concerns, and expectations regarding desalinated water.

### *Water Consumption and Quality of Desalinated Water*

The survey results show diverse patterns of desalinated water consumption behavior among respondents. Specifically, 46% of respondents reported using desalinated water, 32% had never tried it, and 22% were unaware of the source of their water consumption. The selection of drinking water origins showed different choices among the respondents. Bottled water stood as the leading choice for water among interviewees because 46% of survey participants chose it over tap water and other sources that amounted to 26%. The main methods of drinking water acquisition included wells at 24% consumption and wells as the main source at 4%.

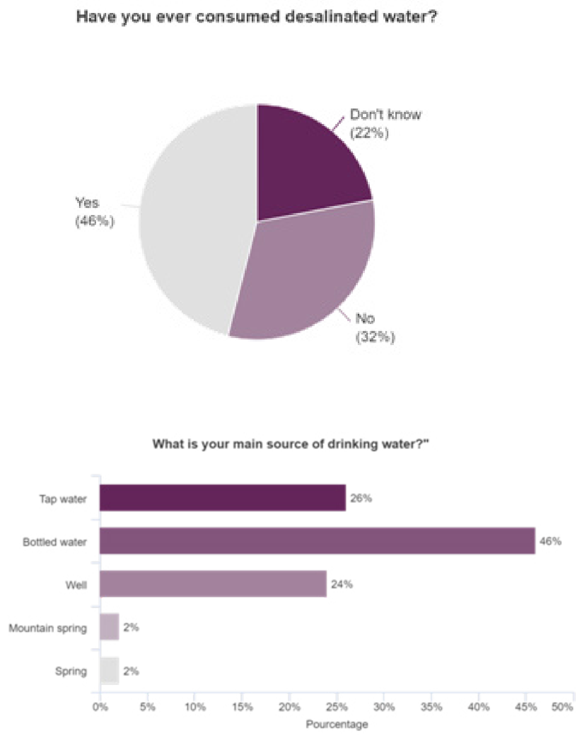



**Figure.10** *Behavioral Determinants of Household Use of Desalinated Water*
*Source: Author's elaboration*

Respondents expressed varying opinions regarding the quality of desalinated water. The findings indicate that 10% rated it as very poor, while 24% considered it poor. The majority, 54%, described the quality as average, while 10% assessed it as good and only 2% considered it excellent. When asked to compare desalinated water to groundwater or water from dams, 28% believed it was inferior, while 18% judged it to be of better quality. These mixed responses suggest a general skepticism or limited confidence in the consistency of desalinated water quality, potentially shaped by regional differences or past experiences.

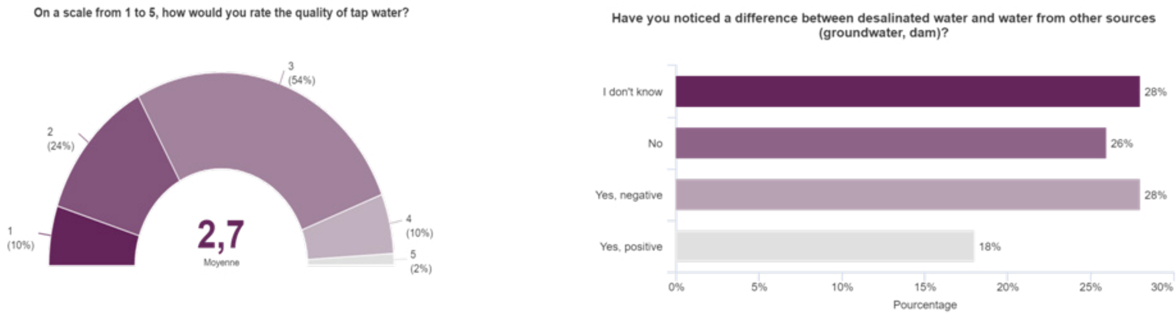



**Figure.11** *Quality of Desalinated Water*
*Source: Author's elaboration*

## *Household Confidence and Willingness to Pay*

Survey participants display very different levels of confidence when it comes to desalinated water quality. Safety and quality perceptions regarding desalinated water are confident for 28% of respondents, while 42% show uncertainty, and the remaining 30% keep an impartial stance. A large population of 86 percent shows interest in paying higher costs for enhanced tap water standards; however, 14 percent reject any increase in prices. A significant portion of 30% respondents find an offer of less than 30 DZD per m3 acceptable to improve water quality. In comparison, 44% bargain between 30 and 50 DZD, 16% agree on prices between 50 and 80 DZD, and 4% are comfortable with prices over 80 DZD.

## *Switching from Bottled Water to Desalinated Water*

This study analyzed how better quality desalinated water would impact the demand for bottled water. Survey participants showed that 60% would replace their bottled water purchases with desalinated water if its quality could be enhanced, but 22% were undecided. In comparison, 18% would continue using bottled water in any case. A wide range of expenditures on bottled water exists among the study participants per month. Among respondents surveyed about their monthly bottled water expenditures, approximately 33% invest between 1,000 and 2,000 DA, followed by 21% who allocate 500 to 1,000 DZD, and 19% who spend less than 500 DZD. In contrast, 27% spend more than 2,000 DZD.

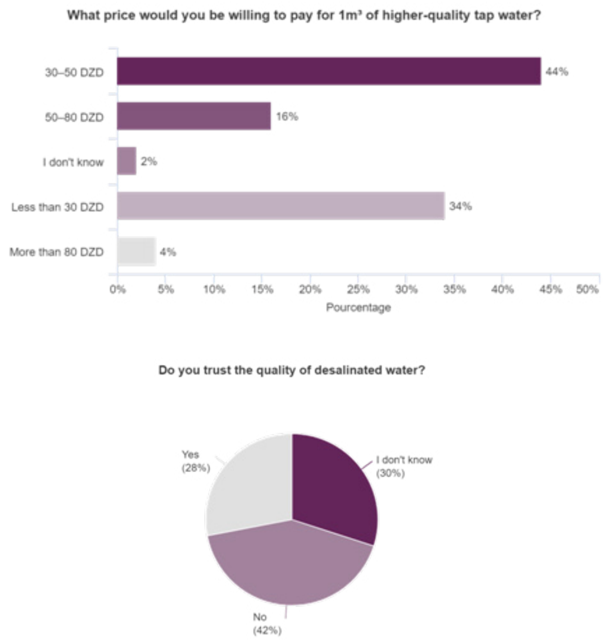



**Figure.12** *Trust in Water Services and Financial Willingness*
*Source: Author's elaboration*

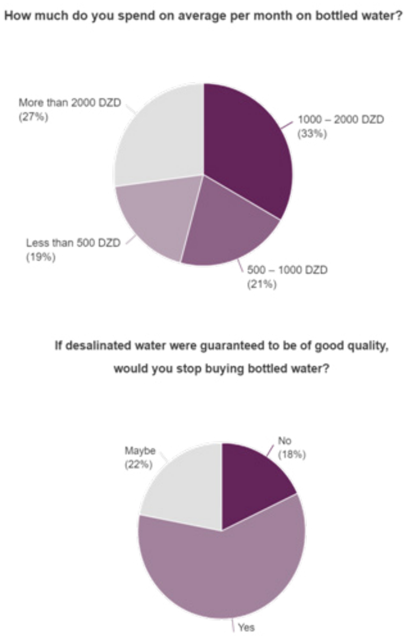



**Figure.13** *Behavioral Determinants of Household Use of Desalinated Water*
*Source: Author's elaboration*

### *Perception of Technology and Support for Desalination Policy*

Public perception of desalination as a solution to water concerns was evaluated through a survey. Desalination proves suitable according to an overwhelming majority 86% though 8% disapprove of using this method. The majority of people surveyed, 86% advocate for increased governmental financing of desalination projects, since 2% oppose additional investment.

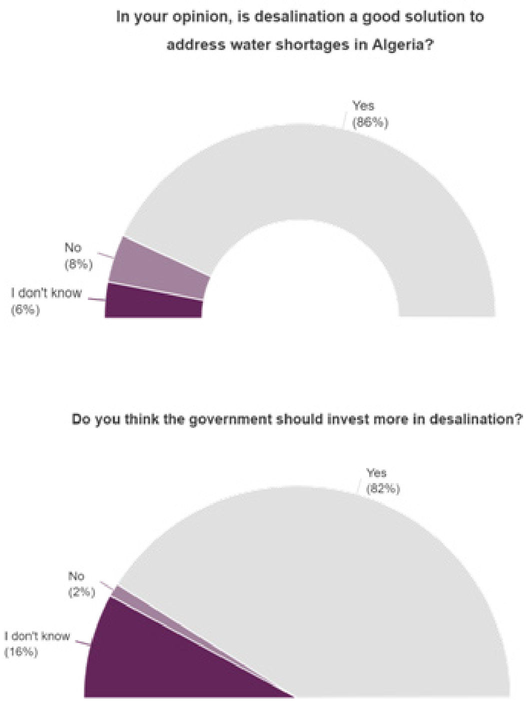



**Figure.14** *Community Attitudes Toward Desalination Technology and Policy*
*Source: Author's elaboration*

The respondents find the prices for tap water to be satisfactory, with 82% considering them appropriate, while 8% see them too high and 10% believe they are insufficient. The research findings enable government officials to understand public water expectations, which direct their water resource management choices in Algeria.

## CHALLENGES AND RECOMMENDATIONS

Discharge of brine from desalination presents significant environmental and cost obstacles to the development of desalination as a potential solution to extreme water shortages in dry areas. To increase the use of desalination as a climate adaptation strategy, we must utilize renewable power sources (e.g., solar, wind) to alleviate costs and lower carbon emissions. Secondly, we need to enact stringent environmental regulations, including environmental assessments. Also, we must integrate water-use efficiency systems and minimize water losses in our water management policies. An effort to expand inland desalination, accompanied by efficient water transport systems, along with a closer integration with wastewater treatment, could afford some dilution of waste brine. Alternatively, the potential reuse of brine waste as commodity chemicals or in aquaculture would be of additional benefit. Importantly, we should prioritize our research and development efforts on these technologies to benchmark, lower cost, and further clarify water quality and thus safety issues. Implementing best practices that align with biophysical site selection for discharge (columnar water depth and high current) can help mitigate environmental costs. Assistance programs for financing are necessary to ensure operational costs are affordable and to reduce equity issues.

The pricing of water itself can change (and often does) to reflect the values placed on the infrastructure needed for these services. Expanding potable water capabilities through desalination for domestic use in water-limited areas is crucial for meeting the future needs of the global population. By improving community consumer confidence in tap water services, we can challenge the bottled water sector.

As a practical recommendation, we advise:

1. The pilot projects in Algeria, which connect solar power to desalination, for example, the solar-powered desalination plant in Hassi R'Mel, demonstrate how reducing fossil fuel consumption can contribute to sustainable desalination processes. With additional renewable energy input, operational costs and carbon emissions would be reduced.
2. There is an urgent need for the Algerian government to enhance regulation and enforcement of new and existing desalination plants, thereby protecting coastal environments in their proximity.
3. Start using best practices, such as brine mixing with treated wastewater or using brine for salt extraction, to minimize harm to marine ecosystems.
4. Expanding initiatives of public surveys around water quality will build trust in desalinated water.
5. Introducing a tiered pricing system linked to water quality improvements, aligned with public willingness to pay (as found in surveys), can finance better treatment without social backlash.

## CONCLUSION

The strategic adaptation of water management in Algeria must extend over the long term because the country faces challenges from reduced resources and population growth that threaten drinking water sustainability and accessibility. Water stress, together with shortages, has affected Algeria for multiple decades due to its restricted water resources across the country. The high cost and energy usage of seawater desalination offer a necessary solution to satisfy expanding water demands within coastal settlements as well as metropolises.

The solution poses several challenges. The process of desalination leads to concentrated brine production that presents substantial environmental harm to marine life, for instance, in cases of unregulated brine disposal. High expenses from desalination projects extend through capital investment costs, together with operating energy costs, thus making the sustainable implementation of this technology challenging. Multiple actions need to be implemented to resolve existing challenges. Adopting solar and wind power as renewable energy sources for desalination plants allows for a reduction in carbon emissions and creates a more eco-friendly process. Environmental regulations require expansion with strict impact assessments to follow before new facilities receive construction authorization. Implementing efficient water management systems and techniques to reduce leaks through dilution methods for brine discharges will help mitigate the negative impact of this technology.

The government of Algeria provides significant funding for building water infrastructure through its investments. The water pricing system requires modification to ensure fair and efficient access to water distribution. The introduction of support systems should lower desalinated water costs for broad sections of users while promoting better water usage habits.

While seawater desalination represents an effective solution to Algeria's water shortages, the adoption of an integrated approach that combines technological innovation, rigorous resource management, and sustainable financing strategies will resolve the problem sustainably. Research and innovation in desalination, water resource management, and pricing policies are the principal axes to secure a future where every citizen has access to quality drinking water while preserving the environment and optimizing available resources.

# CAN DESALINATED WATER DRIVE AGRICULTURAL GROWTH IN ALGERIA? A FEASIBILITY STUDY FOR ECONOMIC AND SUSTAINABLE DEVELOPMENT

AUTHORS : HADJER BOULILA, SEYF EDDINE BENBEKHTI, SALAH EDDINE SARI HASSOUN


Landscape in the province of Jaén, Spain © Borisb17

## Abstract

Algeria faces severe water scarcity, constraining agricultural productivity and food security. While desalinated water currently supports urban needs, it has not been leveraged for agriculture, primarily due to economic and logistical challenges. This study explores the potential for desalination to enhance agricultural resilience, addressing regional water challenges and supporting Algeria's progress toward SDG targets. The aim of this study is to evaluate the feasibility and economic, social and environmental implications of using desalinated water in Algerian agriculture through a Computable General Equilibrium (CGE) model, calibrated with an Environmentally Extended Social Accounting Matrix (EE-SAM) derived from an updated 2023 Input–Output Table.

Three scenarios are explored: (1) status quo with desalinated water restricted to urban uses; (2) reallocation of existing desalinated supply to agriculture; and (3) expansion of desalination capacity to meet new agricultural demand. Results show that agricultural integration boosts total output, labor income, and rural employment, supporting SDGs related to hunger, water use efficiency, and climate resilience. However, increased brine discharge and energy demand highlight environmental trade-offs. These insights inform the design of integrated water–agriculture strategies in arid economies. Keywords: desalinated water, Agriculture, water scarcity, Computable General Equilibrium model, SDGs, Algeria.

# INTRODUCTION

## *Statement of research*

Water scarcity is one of the most pressing challenges facing Algeria, particularly in the agricultural sector, which accounts for 64% of total water withdrawals and employs nearly 11% of the labor force (FAO, 2023; World Bank, 2022). Agriculture remains a cornerstone of rural livelihoods and food security, but it is increasingly strained by climate variability, groundwater overuse, and population pressures. Algeria's renewable internal freshwater resources have dropped to less than 300 $m^3$ per capita per year, far below the water scarcity threshold of 500 $m^3$ (World Bank, 2022). These structural constraints have led to declining agricultural productivity and increased vulnerability in rural areas, threatening both national food resilience and socio-economic stability.

At the same time, Algeria has invested significantly in desalination infrastructure, positioning itself as one of the leading countries in the Mediterranean in terms of desalination capacity. By the end of 2024, the country plans to produce 3.7 million cubic meters of desalinated water per day, meeting 42% of its population's needs (Reuters; 2024). These plants, primarily designed to meet urban and industrial water demands, produce millions of cubic meters of freshwater annually. However, despite the proven capability of desalination to address water scarcity, its potential to support agriculture, a sector that accounts for the majority of water consumption, remains unexplored.
The barriers to desalinated water use in agriculture are multifaceted. Economic constraints, including the high costs of production and energy requirements, pose significant challenges. Logistical issues, such as the transportation of desalinated water to inland agricultural areas, further complicate its application (Martínez-Álvarez et al., 2019). Moreover, environmental concerns, including high energy consumption, potential climate change impacts, and brine disposal, raise concerns about its alignment with sustainable development goals (SDGs) (Sewilam & Nasr, 2017; Zolghadr-Asli et al., 2023). In addition, from a technical standpoint, desalinated water is often deficient in essential ions like magnesium ($Mg^{2}$ ) and calcium ($Ca^{2}$ ), which are critical for crop development, particularly vegetables and fruiting plants (Shaffer et al., 2012). This mismatch requires costly post-treatment or blending with mineral-rich water sources to meet agricultural standards. These cumulative challenges have left a critical gap in research and policy regarding the feasibility and sustainability of desalinated water for agricultural use. These challenges have left a critical gap in research and policy regarding the feasibility and sustainability of desalinated water for agricultural use in Algeria.

This study seeks to address this gap by exploring whether desalinated water can be a viable solution to enhance agricultural productivity and resilience in Algeria. Drawing on successful international examples, such as Spain, where desalination has supported agricultural development, this research evaluates the economic, environmental, and social impacts of integrating desalinated water into Algeria's agricultural sector. Using advanced analytical tools, including Social Accounting Matrices (SAM) and static Computable General Equilibrium (CGE) modelling, this study provides a comprehensive framework for assessing the feasibility of desalinated water in agriculture and offers evidence-based recommendations for sustainable water management. By addressing the intersection of water scarcity, agricultural sustainability, and economic resilience, this research contributes to the broader discourse on sustainable development in water-scarce regions.

## *Literature review*

The use of desalinated water in agriculture is a multifaceted issue that requires a comprehensive assessment to address the interrelated challenges of climate, water, energy, and food security. The climate-water-energy-food (CWEF) nexus has been proposed as a framework to evaluate the potential and challenges of desalination for irrigation, emphasizing the need to consider social, economic, and environmental factors holistically (Zolghadr-Asli et al., 2023). This approach is particularly relevant for understanding the trade-offs and synergies associated with desalination, such as balancing water resource availability with energy consumption and agricultural productivity.

A complementary framework is the Water-Energy-Food (WEF) nexus, which focuses on optimizing resource use to achieve water and food security while maintaining energy sustainability. Several studies highlight that desalination—especially when powered by renewable energy—can contribute to sustainable water supply systems for agriculture, but its feasibility depends on local economic and environmental conditions (Abdelzaher et al., 2023; Drouiche et al., 2022; Mostefaoui et al., 2024). These findings emphasize the need for context-specific assessments that consider the full life-cycle impacts of desalination, including brine disposal and carbon intensity.

To measure agricultural sustainability, the Sustainable Accounting Matrix (SAM) offers a quantitative framework for assessing national performance indicators. By revealing trade-offs and synergies across economic, environmental, and social dimensions, this tool provides valuable insights into the sustainability of agricultural practices, including irrigation strategies involving desalinated water (Zhang, Zhao, et al., 2021). The matrix highlights critical areas where improvements in one dimension (e.g., agricultural productivity) may come at the expense of another (e.g., environmental footprint), emphasizing the importance of balanced policy design.

For developing countries, the Social Accounting Matrix (SAM) has proven to be an effective tool for evaluating the economic impacts of policy interventions, particularly in the agri-food sector. A notable example is the Kenya SAM 2014, which demonstrated the primary sector's capacity to generate value-added production and employment, especially for rural households engaged in semi-subsistence agriculture (Mainar Causapé et al., 2020; Zhang, Yao, et al., 2021). By capturing the interlinkages between sectors, households, and external factors, SAMs provide a robust foundation for assessing the economic feasibility and broader impacts of integrating desalinated water into agriculture.

Together, these frameworks the CWEF[1] nexus, the Sustainable Agriculture Matrix, and the Social Accounting Matrix offer complementary approaches to evaluate the sustainability and feasibility of agricultural practices involving desalinated water (Zhang, Yao, et al., 2021). They enable comprehensive analyses of the economic, environmental, and social dimensions of desalination, supporting evidence-based policy design for sustainable agriculture. This study builds on these frameworks to explore the potential of desalinated water in Algeria's agricultural sector, addressing the unique challenges posed by water scarcity, energy demands, and socio-economic development.
Despite growing interest in desalinated water as a solution for water-scarce regions, there are significant methodological gaps in assessing its feasibility and sustainability for agricultural use, particularly in Algeria and other mediterranean countries, where desalination is not yet applied in agriculture. Existing research often lacks integrated economic-environmental models capable of simultaneously assessing financial feasibility, energy demands, and environmental impacts, such as emissions. Additionally, and to the best of our knowledge, this study is the first to explore SAM and CGE modelling in this context. Furthermore, the research aligns with Algeria's commitments to the Sustainable Development Goals (SDGs), particularly those focused on clean water access (SDG 6), climate action (SDG 13), and sustainable agriculture (SDG 2) which provides a foundation for developing integrated water management strategies that balance economic, environmental, and social goals.

## METHODOLOGY

This study combines a Social Accounting Matrix (SAM)[2] framework with a static Computable General Equilibrium (CGE) model[3] to evaluate the potential and feasibility of using desalinated water in Algerian agriculture. Given Algeria's current reliance on desalinated water exclusively for urban and industrial purposes, the analysis explores hypothetical scenarios in which desalinated water is allocated to agriculture. This approach is designed to assess potential economic, environmental, and social impacts under Sustainable Development Goal (SDG) criteria using a static CGE model.

This methodology is well suited regarding its ability to:

- Provide detailed assessment of the economy-wide impact of introducing the desalinated water into agriculture.
- Illustrate how different sectors (e.g., desalination, agriculture, energy) and institutions (e.g., households, government) interact and adjust to the policy change.
- Evaluate the economic feasibility of desalinated water use by analyzing impacts on GDP, income distribution, and sectoral outputs.
- It allows for alignment with SDG goals by integrating economic, environmental, and social dimensions (e.g., food security, energy use, emissions).

The figure 01 below illustrates the methodology employed in this study to assess the feasibility and sustainability of using desalinated water in agriculture.

1 The Climate-Water-Energy-Food (CWEF) Nexus is an integrated approach that examines the interconnections between climate change, water resources, energy production, and food security.
2 A Social Accounting Matrix (SAM) is an economic tool that provides a comprehensive snapshot of all transactions within an economy during a specific period, usually one year. It captures the flow of income and expenditures among different sectors, institutions, and factors of production. (Capausé et al.; 2018)
3 A static Computable General Equilibrium (CGE) model is an economic modeling framework used to analyze how an economy reacts to changes, such as new policies or external shocks, at a single point in time. It simulates the economy by capturing the interactions between producers, consumers, government, and international trade, based on microeconomic principles and input data like a Social Accounting Matrix (SAM). (Cassar et al., 2024)

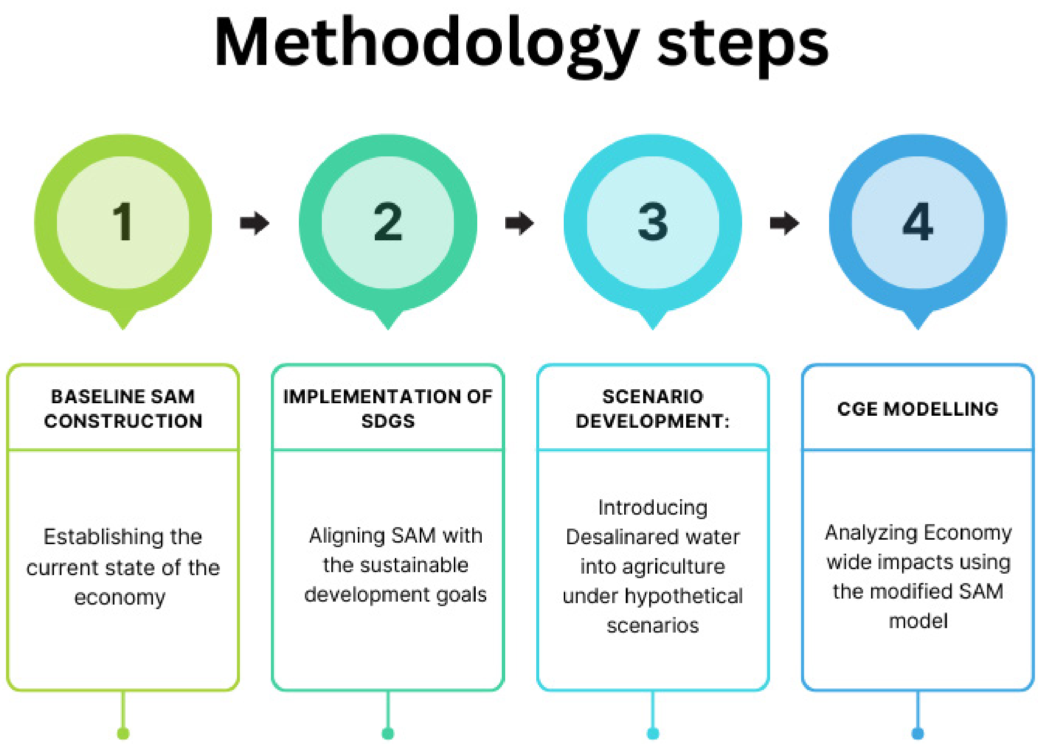



**Figure.1** *Methodology steps*
*Source: by the author's*

## *Algeria Input-Output table (IOT) 2023*

### *The IO_T structure*

The Input-Output Table (IOT) for Algeria was updated from the most recently available version (2015) ((GWS), 2023) to the year 2023 using a structured approach combining national accounts, macroeconomic aggregates (GDP, consumption, investment, trade), sectoral production and employment data, and specialized statistics on desalination capacity, costs, and output from Plan Bleu observatory. The update preserved the structure of the original IOT while integrating a new sector—desalination—reflecting its contribution to water supply for municipal and industrial uses.

### *Updating the IOT*

In order to update the Algerian Input-Output table to 2023, this paper adopted a hybrid method combining the RAS technique[4] (Polenske, 1997; Wang et al., 2015) with macroeconomic extrapolation based on available national accounts and international datasets.

4 The RAS technique is a widely used matrix-balancing method that adjusts an initial input-output matrix to match updated row and column totals, while preserving the internal structure as much as possible. It is named after the three components involved: row adjustments (R), column adjustments (A), and scaling factors (S).

| Step | Methodology | Data Source | Metric (Unit of Measurement) |
|---|---|---|---|
| **Sectoral Output** | Compound annual growth rate (CAGR) | GDP by activity (ONS,World Bank) | Billion DZD (or % growth/year) |
| **Final Demand (HH/Gov)** | Scaled from 2015 proportions | UN National Accounts, CEIC | Billion DZD |
| **Investment** | Proxy: 10% of gross output | Historic trends, Plan Bleu observatory | Billion DZD or % of output |
| **Imports and exports** | Sector mapping and reconciliation | UN COMTRADE (2023), National Accounts | Billion DZD / USD |
| **Desalination Output** | Volume × unit cost (converted to DZD); inputs based on technical shares | Plan Bleu Observatory database (2023), DesalData database from GWI, Author's calculations | $m^3$/day and DZD/$m^3$ |
| **Import Duties** | Effective tariff application per input (e.g., chemicals, equipment) | UN COMTRADE, Algerian Tariff Book | % rate on import value |
| **Price/Currency Update** | Inflation adjusted; exchange rate = 135 DZD/USD | World Bank WDI, CEIC, ONS | Index (base year), DZD/USD |
| **Balancing (RAS method)** | Proportional scaling to enforce Total Use = Total Resources | Author's model; UN SNA methods; Lahr & Mesnard (2004) | Dimensionless (ratios) |

TABLE 1

**Steps of updating the Algeria IOT table 2023**

*Source: by the authors*

## *Building an Environmental Extended Social Accounting Matrix (EE-SAM)*

### *The EE-SAM structure*

The SAM represents the backbone to assess the macroeconomic and environmental implications of desalinated water use across sectors. The EE-SAM built for this study is an extension to the updated IO 2023 to include institutional accounts, factor payments, and environmental extensions and maintains the structure of the 19 sectors organized into four main economic groups.

| Group | Sectors |
|---|---|
| **Agriculture** | Agriculture, forestry, fishing |
| **Manufacture (industry)** | Hydrocarbon industry, Iron and steels, Chemicals, Food industry, Desalination (embedded)[5] |
| **Construction** | Construction materials, building, petroleum services... |
| **Services** | Water and energy, Public Works, Business Services, Transport, Government Services |
| **Environment**[6] | Brine discharge, Energy consumption, CO2 emissions |

TABLE 2

**Sectoral Grouping Used in the Algerian Input-Output Table and Environmental Extension (2023)**

*Source: by the authors*

5 Although the Desalination sector is embedded in the Manufacturing group in the current IOT and SAM, the model tracks its outputs, inputs, and environmental flows separately. This allows the simulation of reallocation policies (e.g., from urban to agricultural use) and captures their macroeconomic and environmental implications.

6 These indicators are not monetary transactions but are structurally linked to the production sectors, enabling the model to assess the environmental trade-offs of policy changes. This allows for the analysis of sustainability dimensions — such as emissions intensity or water-related externalities — without distorting the economic accounting balances of the SAM. However, certain qualitative environmental externalities—such as marine ecosystem disturbance, cumulative toxicity, or operational noise—are not captured within the accounting framework. These effects are highly site-specific and are better addressed through complementary environmental assessments or physical models rather than monetary flow analysis.

This integrated EE-SAM structure provides a robust base for policy dialogue on sustainable water governance, green growth, and food-energy-water security in Algeria.

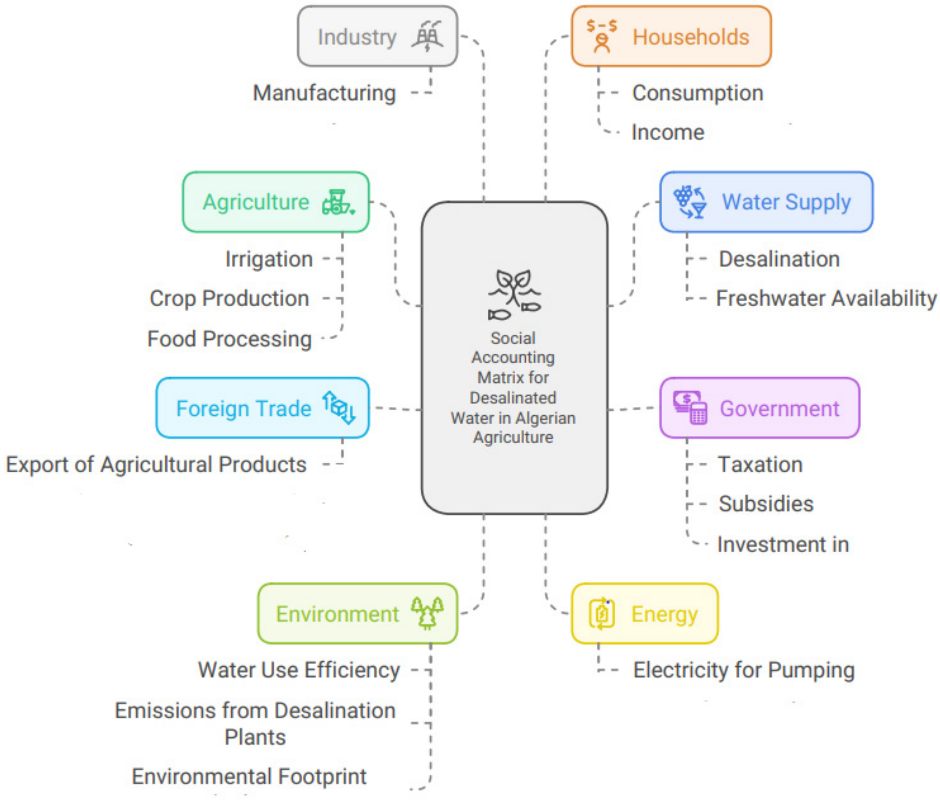



**Figure.2** *Conceptual Framework for the Relation Between Desalinated Water, Agriculture, and Sustainable Development in Algeria*
*Source: by the authors*

Figure (2) illustrates a conceptual framework using a Social Accounting Matrix (SAM) approach to analyze the potential integration of desalinated water into Algerian agriculture. It shows the interactions between key sectors (agriculture, water supply, energy, industry, households, government, foreign trade, and the environment) within the context of economic, environmental, and social sustainability. The diagram reflects the study's focus on how desalinated water could enhance agricultural productivity, support food security, and contribute to Algeria's progress toward Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action). The framework also captures economic flows, energy usage, emissions, and the role of government policies and foreign trade in this process.

### *Scenarios for Policy Simulation*

Three policy scenarios are built into the model and summarized in table (03):

| Scenario | Water Use Configuration | Policy Focus | Expected implications |
|---|---|---|---|
| **Scenario1 (Baseline scenario)** | Desalinated water allocated to urban needs only | Baseline — current use case | Limited economic transformation; agriculture remains water-constrained; no improvement in food production or jobs. |
| **Scenario 2** | Desalinated water reallocated to agriculture | Alternative — food security and water resilience | Output and job gains in agriculture through improved irrigation; minor trade-offs in urban service sectors; neutral total supply; no added environmental pressure |
| **Scenario 3** | Increased desalination capacity with 10% allocated to agriculture | Forward-looking expansion for agri-food systems | Stronger agricultural and manufacturing growth; enhanced rural employment; environmental pressures increase. |

**TABLE 3**
**Scenarios for Policy Simulation**
*Source: by the authors*

The baseline scenario represents Algeria's current economic structure, where desalinated water is allocated solely to urban and industrial sectors, with no flows to agriculture. This SAM captures existing economic flows and resource allocations across key sectors, including agriculture, desalination, energy, households, and government. While this setup ensures short-term service stability, it limits the agricultural sector's ability to overcome water constraints, making it vulnerable to climate variability and reducing its contribution to food security and rural livelihoods. The baseline serves as a reference point to assess the trade-offs and opportunities presented by alternative water allocation strategies. The second scenario aims to evaluate how desalinated water affects agricultural output, factor income, water productivity and environment pressure where it assumes that a 10% of desalinated water produced will be reallocated from service-oriented services towards agriculture. This reallocation is translated in the SAM by adjusting the intermediate consumption vector of the agricultural sector to include desalination-based water inputs. This scenario is expected to improve agricultural output and employment, while potentially reducing service-sector gains — reflecting a trade-off in resource use. These effects are quantified in the results section that follows.

The third scenario introduces a forward-looking strategy by assuming that Algeria increases its total desalination capacity, and that 10% of this new capacity is allocated exclusively to agriculture. This additional supply is incorporated in the SAM as an increase in both the desalination sector's output and agriculture's intermediate consumption. Unlike Scenario 2, this configuration avoids reallocation from urban needs, thereby bypassing any trade-offs. It is expected to generate stronger gains in agricultural output, employment, and overall GDP, while increasing energy use and brine discharge — impacts that are analyzed in detail in the following section. This scenario also aligns with Algeria's national water strategy, which aims to expand desalination production to 3.7 million $m^3$/day as part of long-term water security efforts (Reuters, 2024). By dedicating a portion of this expansion to agriculture, the country could support climate-resilient food systems while reducing pressure on groundwater and surface sources. The rationale for this expansion is reinforced by increasing environmental pressures: indicators from Plan Bleu's Mediterranean Observatory show a rise in consecutive dry days, soil moisture depletion, and water stress levels under the RCP4.5 climate pathway. By dedicating a portion of this expansion to agriculture, the country could support climate-resilient food systems while reducing pressure on groundwater and surface sources.

### CGE model structure and equations:

Using the IOT and SAM, a static small open economy CGE model is employed to analyze the economy-wide impacts of desalinated water in agriculture. This static CGE model, which relies on a single-period snapshot, simulates the economic and sustainability effects of introducing desalinated water into agricultural production without requiring time-series data especially in light of limited historical data in the field.

The CGE model is structured using a system of equations, inspired by standard general equilibrium frameworks. (Dellink et al., 2020; Hosoe et al., 2010; Lofgren et al., 2002) incorporating nested production, Armington trade, and institutional behavior(Fullerton & Ta, 2019; Ji et al., 2022).

### Production Function (Cobb-Douglas):

$$Q_i = A_i \cdot L_i^{\alpha_i} \cdot K_i^{1-\alpha_i}$$

Where:

- $Q_i$ is the output of sector i
- $A_i$ is a total factor productivity term,
- $L_i$ and $K_i$ are labor and capital inputs,

$\alpha_i$ is the labor share in value-added. Each sector i produces output $Q_i$ using labor $L_i$ and capital $K_i$. The share parameters $\alpha_i$ reflect sector-specific labor intensity. This function assumes constant returns to scale and unit elasticity of substitution (Cobb-Douglas).

The Cobb-Douglas production function is applied to all sectors included in the model, but special focus is placed on three water-relevant sectors: (1) agriculture (as the receiving sector of desalinated water), (2) desalination (embedded within the manufacturing group), and (3) public water distribution (included in the services group). The function captures capital–labor interactions, while the desalinated water input enters as part of the intermediate demand vector in the SAM, not directly in the value-added component. This allows us to model desalinated water's effect on output and employment in agriculture, while preserving the standard structure of CGE production functions.

### Factor Demand:

Firms minimize production costs:

$$C_i = w \cdot L_i + r \cdot K_i$$

Where:

- $C_i$ is total cost of production in sector i,
- w is the wage rate,
- r is the return to capital,
- $L_i$,$K_i$ are input demands for labor and capital.

Given wage w and return to capital r, factor demand derives from cost minimization subject to the production function.

### Household Income:

$$Y_H = \sum_i w_i L_i + \Pi + TR$$

Where:

- $Y_H$ is total household income,
- $w_i . L_i$ is labor income,
- is capital income (profits),
- $\Pi$ ? is transfers from government, firms, or the rest of the world.

Total household income $Y_H$ comes from labor income, capital profits , and transfers TR.

This equation captures how income changes for households, particularly rural ones, as agricultural activity expands due to improved water availability.

### Household Consumption (Linear Expenditure System):

$$C_i = \beta_i \cdot Y_H$$

Where:

- $C_i$ is household demand for good i,
- $\beta_i$ is the marginal budget share,
- $Y_H$ is household income.

Households allocate income among goods based on marginal budget shares $\beta_i$. As households experience income changes from sectoral shifts (notably agriculture), this equation reflects how demand for goods and services adjusts accordingly. The Linear Expenditure System (LES) captures essential and marginal spending patterns. In this model, desalinated water is treated as a regular consumption good within the LES framework, particularly for urban households. Its demand is thus governed by a marginal budget share ßi\beta_ißi, reflecting its increasing role in meeting basic water needs under scarcity conditions.

## Trade (Armington Assumption)[7]:

$$Q_i^D = \left(\delta_i M_i^{-\rho} + \left(1 - \delta_i\right) D_i^{-\rho}\right)^{-\frac{1}{\rho}}$$

Where:

- $Q_i^D$ is total domestic demand for good i,
- $M_i$ and $D_i$ are imports and domestically sourced goods,
- $\delta_i$ is the Armington share parameter,
- $\rho$ is the substitution parameter between imports and domestic goods.

Domestic demand $Q_i^D$ is a CES aggregate of imports $M_i$ and domestic goods $D_i$, allowing imperfect substitution (Armington, 1969).

## Market Clearing:

$$Q_i = C_i + I_i + G_i + E_i - M_i$$

Where:

- $Q_i$ is total output of good i,
- $C_i$, $I_i$, $G_i$ are household, investment, and government demand,
- $E_i$ is exports, and $M_i$ is imports.

Total output is absorbed by household consumption, investment, government demand, exports $E_i$, and net imports.

## Environmental Satellite Equation[8]

To account for desalination-related environmental flows without altering market equilibrium, an environmental satellite identity is included in the model. Total generation is calculated as a function of sectoral output:

$$E_k = \sum_i \gamma_{ik} \cdot Q_i$$

Where:

- $E_k$ is the total quantity of environmental output k (e.g., brine, emissions),
- $\gamma_{ik}$ is the environmental coefficient for sector i,
- $Q_i$ is sectoral output.

where $\gamma_{ik}$ is the sector-specific emission or resource-use coefficient (e.g., m3 of brine per unit of output, CO2 emissions), and $Q_i$ is total output from sector i. This formulation allows the model to quantify environmental trade-offs associated with production and policy scenarios, without introducing feedback loops into prices or decisions. The approach is consistent with established CGE-ENV modeling practices (Böhringer & Rutherford, 2008; Burniaux & Truong, 2002; Lofgren et al., 2002).

## Model Calibration and Closure Assumptions.

The model is calibrated[9] to the 2023 Environmentally Extended Social Accounting Matrix (EE-SAM) of Algeria, developed for this study. This SAM incorporates desalination as a distinct production activity and quantifies environmental flows such as brine discharge and energy use. Calibration follows the standard static CGE approach, where initial equilibrium values are taken from the SAM, and behavioral parameters are set based on literature and regional proxies. The closure rules adopt an investment-driven macroeconomic closure, where investment is savings-driven, government savings are fixed, and the trade balance is endogenous. Labor is segmented by sector with fixed nominal wages,

7 The Armington specification models the imperfect substitution between domestic and imported goods. It is particularly relevant in this study to assess how increased domestic agricultural production, made possible by desalinated water, can reduce reliance on food imports.
8 This satellite equation links sectoral output to environmental outcomes, such as brine generation or energy-related emissions. It enables tracking of desalination's environmental impacts under each scenario without feeding back into behavioral or price decisions, in line with standard CGE-ENV frameworks.
9 The CGE model is calibrated using the 2023 Environmentally Extended SAM (EE-SAM), which provides a complete snapshot of the Algerian economy, including production, factor payments, institutional income, and trade flows. All share parameters (e.g., cost shares, budget shares, trade substitution parameters) are directly derived from the SAM using zero-profit and market-clearing conditions. The Cobb-Douglas production function implies unitary elasticity of substitution between labor and capital, and the Linear Expenditure System (LES) uses average budget shares to determine marginal shares. For the Armington CES function, elasticity of substitution values are drawn from literature benchmarks and finally Environmental coefficients are based on technical data from Plan Bleu, GWI, and relevant engineering studies.

allowing employment levels to adjust. Capital is fully employed and mobile across sectors.
A table summarizing all parameters and elasticities is provided in Annex Table A1 which also includes sector-specific production coefficients used in the CGE calibration.

Finally, after the calibration process, The CGE model runs baseline versus scenario comparisons, where policy shocks introduce desalinated water into agriculture, enabling analysis of its effects on GDP, household income, and sectoral outputs. SDG-aligned impacts are tracked across key dimensions: economic viability (SDG 8), environmental sustainability (SDG 6 and SDG 13), and social benefits (SDG 2 and SDG 12).

## RESULTS

This section presents the key findings derived from an environmental extended CGE model which has been calibrated using standard elasticities and closure rules based on Algeria's 2023 Social Accounting Matrix. The key elasticity values, sectoral coefficients, and closure assumptions are summarized in the annex covering key sectors such as agriculture, desalination, manufacturing, and services. This calibration ensures internal consistency in the SAM and supports scenario-based simulations with comparative insights.

Three scenarios are examined: the baseline (Scenario 1), where desalinated water is used exclusively for urban and service-related needs, and an alternative (Scenario 2) and and a dedicated-use case (Scenario 3), where future desalination units are assumed to serve agriculture entirely. The results focus on changes in sectoral output, value-added, household income, and environmental pressures such as brine discharge and energy use. These findings provide early insights into the economic and sustainability trade-offs associated with alternative water allocation strategies. The results focus on changes in sectoral output, value-added, household income, and environmental pressures such as brine discharge and energy use. These findings provide early insights into the economic and sustainability trade-offs associated with alternative water allocation strategies.

### *Scenario-Based Impacts on Output, Income, and Environmental Pressure*

This section examines the impact of desalination on the key indicators : sectoral output, value-added, labor income and environmental pressure through both scenarios. Results are summarized in table (04) and figure (03).

| Indicator | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| **Agriculture Output** | 50.10 B DZD | 53.02 B DZD | 55.63 B DZD |
| **Manufacturing Output** | 19.91 B DZD | 21.90 B DZD | 19.91 B DZD |
| **Total Output** | 70.95 B DZD | 74.93 B DZD | 74.03 B DZD |
| **Value Added (GDP Proxy)** | 40.58 B DZD | 42.77 B DZD | 43.33 B DZD |
| **Labor Income** | 28.93 B DZD | 30.41 B DZD | 30.98 B DZD |
| **Brine Generated** | 50,000 $m^3$ | 55,000 $m^3$ | 65,000 $m^3$ |
| **Energy Consumption** | 1.6 GWh | 1.76 GWh | 2.08 GWh |
| **CO2 Emission** | 864 tons $CO_2$ | 950.4 tons $CO_2$ | 1,123.2 tons $CO_2$ |

TABLE 4
**Comparison of key economic and environmental indicators under current and reallocated desalination use (Scenarios 1 and 2).**
*Source: Author's simulation based on 2023 EE-SAM*

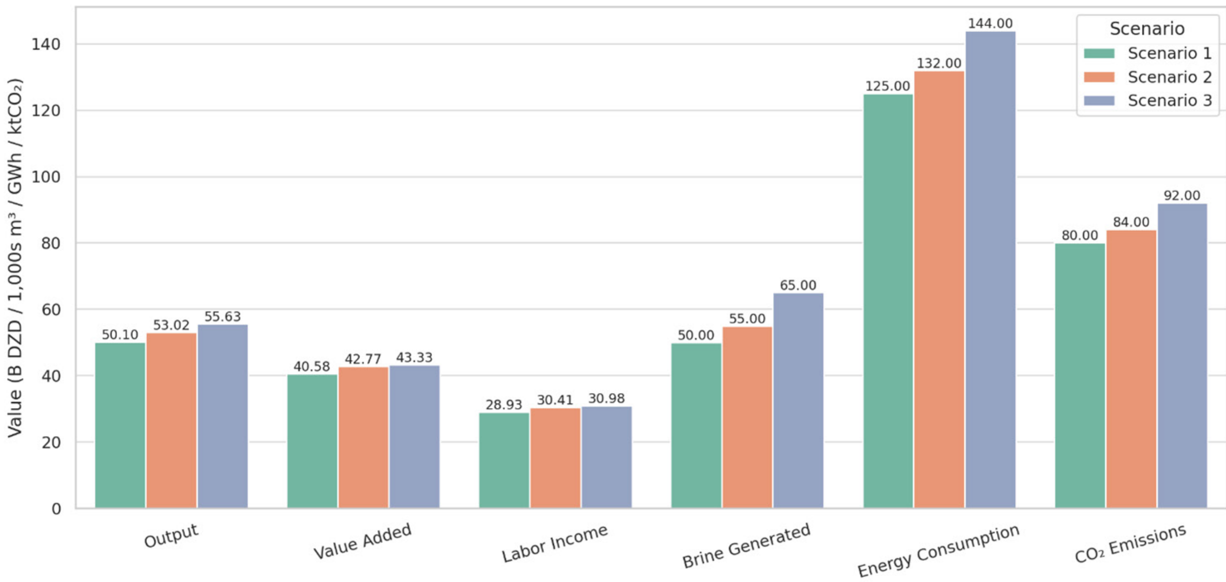



**Figure.3** *Sectoral and environmental Effects of Water Reallocation*
*Source: Author's simulation based on 2023 EE-SAM*

Note: The values presented in Table (04) represent annual aggregate outcomes based on a static CGE simulation calibrated to Algeria's 2023 economy. All output, value-added, and income figures are expressed in billion Algerian dinars (B DZD), at basic prices, and reflect a one-year impact resulting from reallocation or expansion of desalinated water use under each scenario. These are not projections over time but rather comparative static results that help assess the immediate economic and environmental effects of alternative desalination integration strategies. The environmental indicators—brine discharge, energy consumption, and $CO_2$ emissions—are annualized estimates linked to desalination output as defined in each scenario's assumptions.

The simulation results summarized in Table (04) and Figure (03) offer a comparative overview of the sectoral and environmental impacts of alternative desalinated water allocation strategies. Moving from exclusive urban use (Scenario 1) to agricultural integration (Scenarios 2 and 3)— first through reallocation, then through additional production. These figures reveal evolving trade-offs between economic gains and environmental pressures. In particular, the coupling of desalination with agricultural use accentuates sustainability concerns related to brine discharge and energy intensity. These dynamics are further explored as follows:

### *Sectoral Output and Value Added*

Comparing across the three scenarios, the reallocation and expansion of desalinated water reveal differentiated sectoral gains. Moving from **Scenario 1 to Scenario 2,** where a portion of urban desalinated water is diverted to agriculture, results in a 2.92 billion DZD increase in agricultural output and a 1.99 billion DZD increase in manufacturing output, totaling 3.98 billion DZD in national production. This reallocation significantly boosts **value-added** by 2.19 billion DZD, with agriculture contributing the lion's share due to its stronger domestic input linkages and labor intensity.

Transitioning from **Scenario 2 to Scenario 3**, where an additional 10% desalination capacity is introduced exclusively for agriculture, leads to **further gains in agriculture** (2.61 billion DZD in output) while manufacturing output remains stable. Total output increases by +2.60 billion DZD, and value-added rises by +0.56 billion DZD, reflecting diminishing returns in manufacturing but continued high multipliers in agriculture.

Overall, the results show that **incremental investment in desalination targeted at agriculture** (Scenario 3) produces more sustainable and inclusive economic benefits than merely reallocating existing supplies (Scenario 2). These gains are particularly pronounced in **value-added and labor income**, reinforcing agriculture's strategic role in promoting rural employment and water-efficient growth under Algeria's resource constraints.

### *Desalination's Role and Trade-Offs*

Desalination is increasingly central to Algeria's water security strategy, especially as groundwater sources become depleted and surface water availability fluctuates due to climate variability. However, the modelled scenarios reveal diverging implications. In Scenario 2, reallocating part of the existing desalinated water to agriculture offers economic gains but may unintentionally heighten vulnerability in the urban sector, which is already under-supplied. According to recent government reports, Algeria's current desalination capacity (around 2.5 million m³/day) does not fully meet the growing domestic and urban water demand (Ministry of Water Resources, 2023). Redirecting this limited resource to agriculture could therefore worsen household and service-sector water stress, particularly during summer peaks.

In contrast, **Scenario 3** assumes additional production which is earmarked solely for agricultural use, thus **avoiding direct competition with urban supply**. However, the strategy is not without cost: brine discharge increases by 10,000 m³, and energy use — primarily from fossil sources — intensifies, raising sustainability concerns. The environmental trade-offs of desalination are well-documented: brine toxicity to marine life, risks of cumulative pollution, and significant carbon emissions if powered by non-renewable energy (Jones et al., 2019; UNEP, 2020). These impacts are magnified when desalination is scaled up without integrated environmental safeguards.

Overall, the results suggest that **reallocation without production expansion (Scenario 2)** may be economically attractive but **socially and politically risky,** while **capacity expansion (Scenario 3)** presents environmental challenges that must be addressed through green energy investments, improved brine management, and regulatory oversight. Policymakers must therefore consider not only the sectoral benefits but also the system-wide trade-offs, ensuring that desalination supports both food security and urban resilience without undermining ecological sustainability.

### *Income Distribution and Labor Effects*

The model reveals that reallocation of desalinated water has measurable implications for labor markets and household income. Between Scenario 1 and Scenario 2, labor income rises by 1.48 billion DZD, driven largely by the expansion of the agriculture sector, which is more labor-intensive and domestically embedded. In Scenario 3, where desalination capacity is increased rather than reallocated, labor income rises further by 0.87 billion DZD, confirming that additional water supply generates incremental employment without compromising urban needs.

Agriculture plays a pivotal redistributive role in Algeria's economy, especially in rural areas where underemployment remains high. The shift of water resources toward this sector thus contributes to both output and equity goals, especially as most of the labor gains accrue to low- and medium-skilled rural workers. This is consistent with findings from similar CGE-based studies in water-scarce countries (Calzadilla et al., 2010).

However, the labor effects in the manufacturing sector — where desalination is currently housed — are modest due to its higher capital intensity. In Scenario 2, some of the gains in agricultural labor income are offset by a plateau in manufacturing wages, reflecting the resource competition. In Scenario 3, where no sector sacrifices existing allocations, the income gains are additive, and both agriculture and manufacturing contribute to overall wage growth.

The simulations thus suggest that targeted desalination expansion for agriculture can be a pro-poor strategy, **enhancing rural employment** and **household welfare.** Yet, these benefits are **conditional** on ensuring that **urban supply remains secure** and that the expansion is accompanied by **environmental safeguards** to maintain long-term sustainability.

### *Environmental impact*

The environmental implications of reallocating or expanding desalinated water use are critical, particularly for a water-scarce and energy-dependent country like Algeria. The model incorporates two key environmental indicators: brine discharge and energy consumption, both of which intensify with increased desalination activity.

In Scenario 2, where a portion of existing desalinated water is reallocated from urban to agricultural use, brine discharge increases from 50,000 m³ to 55,000 m³ per day, and electricity use rises by 5,000 MWh/year, resulting in approximately 3,800 additional tons of $CO_2$ emissions annually, based on an emission factor of 0.76 tons $CO_2$/MWh (IEA, 2022).

In Scenario 3, where desalination capacity is expanded and 10% of the new output is directed to agriculture, brine generation increases further to 65,000 m³/day, energy use climbs to 115,000 MWh/year, and associated $CO_2$ emissions are estimated at 87,400 tons annually. This configuration avoids competition with urban water needs but significantly increases Algeria's desalination-related carbon footprint.

Beyond these quantifiable impacts, several non-modeled externalities deserve attention. These include noise from high-pressure pumps, disturbance of natural water intake systems, and long-term coastal and subsurface salinization, particularly when discharge and intake are not adequately regulated (Gude, 2016; UN Environment, 2020). While these externalities are not explicitly captured in the Environmentally Extended Social Accounting Matrix (EE-SAM), they are crucial for holistic impact assessment and should be addressed in future research.

In conclusion, desalination can enable economic diversification and climate-resilient agriculture, but its environmental footprint increases substantially with scale and intensity. Scenario 3, while yielding stronger economic outcomes, underlines the need for parallel investments in brine management technologies, renewable energy integration, and coastal ecosystem monitoring, in alignment with Algeria's National Water Strategy (Ministry of Water Resources and Security, 2023).

### *Institutional distribution of income*

This section explores how the reallocation of desalinated water to agriculture affects the distribution of income and value-added across institutional agents: households, firms, and government. The analysis draws from the factor payment structure and institutional flows in the Environmentally Extended Social Accounting Matrix (EE-SAM), capturing both direct and indirect effects.

| Institution | Scenario 1 | Scenario 2 | Scenario 3 | Key Drivers |
|---|---|---|---|---|
| **Households** | 28.93 B DZD | 30.41 B DZD | 31.28 B DZD | Labor income in agriculture, services |
| **Firms** | 9.81 B DZD | 10.28 B DZD | 10.85 B DZD | Capital income from industry, desal |
| **Government** | 4.62 B DZD | 4.75 B DZD | 4.88 B DZD | Production & VAT growth |

**TABLE 5**
**Income and Redistribution Summary**
*Source: Author's simulation based on 2023 EE-SAM*
***Note: Estimates derived using institutional shares from EE-SAM sectoral value-added and factor income allocations.***

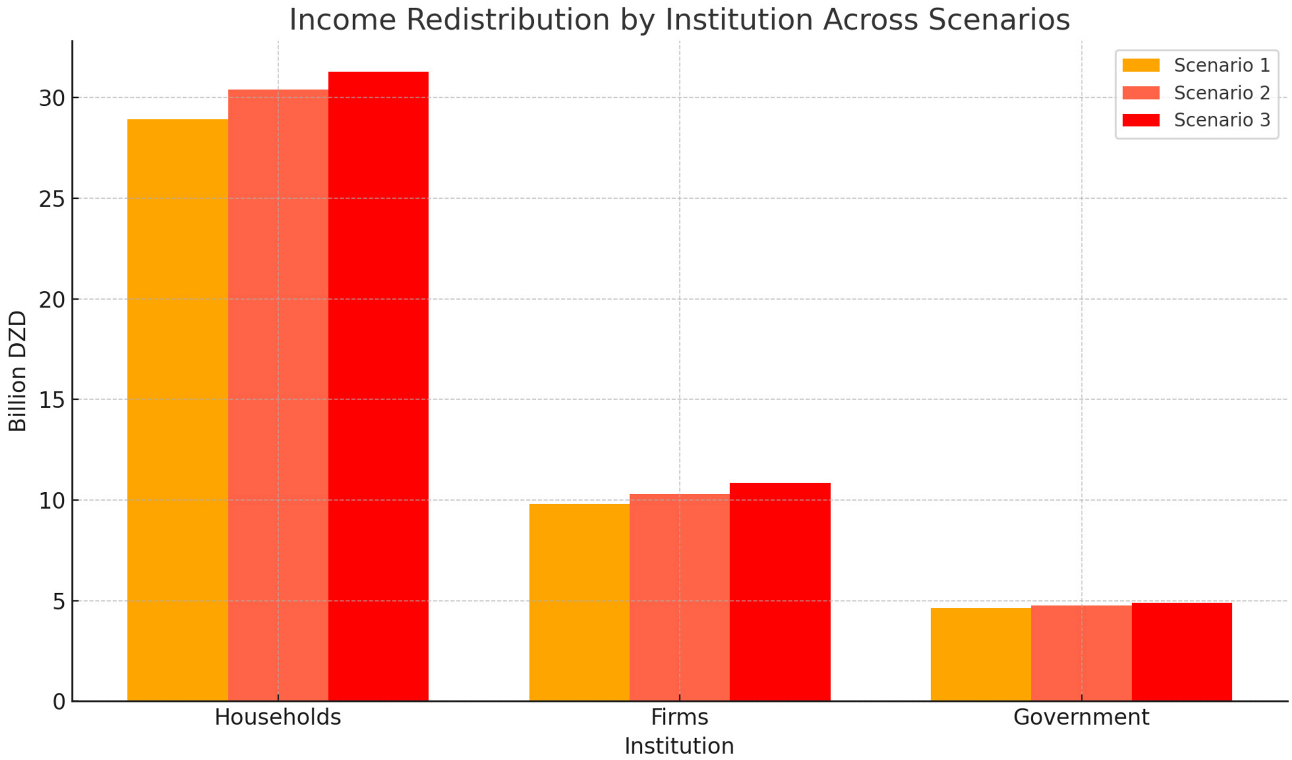



**Figure.4** *Institutional distribution of income*
*Source: Author's simulation based on 2023 EE-SAM*

Table (05) and the associated figure present a breakdown of how income is distributed among major institutional agents — households, firms, and the government — under the three desalination reallocation scenarios. This decomposition sheds light on the socio-economic spillovers of shifting desalinated water from exclusive urban use to agriculture.

Households see the largest gains, with income rising from 28.93 B DZD in Scenario 1 to 30.98 B DZD in Scenario 3. This reflects higher labor demand in agriculture, especially under expanded water access. Firms benefit from increased capital income, growing from 9.81 B DZD to 10.48 B DZD, due to greater industrial and desalination activity, particularly in Scenario 2. Government revenue also improves, reaching 4.88 B DZD in Scenario 3, supported by growth in output and tax-related flows.

Overall, Scenario 3 delivers the most inclusive benefits, marked by the strongest gains in household income due to labor-intensive agricultural expansion and modest yet positive fiscal improvements driven by broader production and VAT growth. However, these socioeconomic gains are accompanied by notable environmental costs, including a 30% increase in brine discharge, higher energy consumption, and elevated $CO_2$ emissions, underscoring the need for integrated safeguards and sustainable planning.

### *Sectoral Multipliers and Linkage Effects*

This study uses Leontief[10] output multipliers derived from the updated 2023 Input–Output Table to assess the strength of inter-sectoral linkages in the Algerian economy. By comparing multipliers across agriculture, manufacturing (including desalination), services, and construction, the analysis highlights which sectors offer the greatest economy-wide returns on resource allocation. These findings are particularly relevant for understanding the systemic impact of reallocating desalinated water, and for identifying policy priorities that support inclusive and sustainable growth.

10 The Leontief output multiplier measures the total increase in economy-wide output resulting from a one-unit increase in final demand for a given sector. It captures both direct and indirect production effects through inter-industry linkages, based on the inverse of the input–output coefficient matrix. In CGE modeling, it is often used as a diagnostic tool to assess sectoral backward linkages and to identify which sectors are most effective at stimulating broader economic activity.
Source: Miller, R.E., & Blair, P.D. (2009). Input–Output Analysis: Foundations and Extensions (2nd ed.). Cambridge University Press.

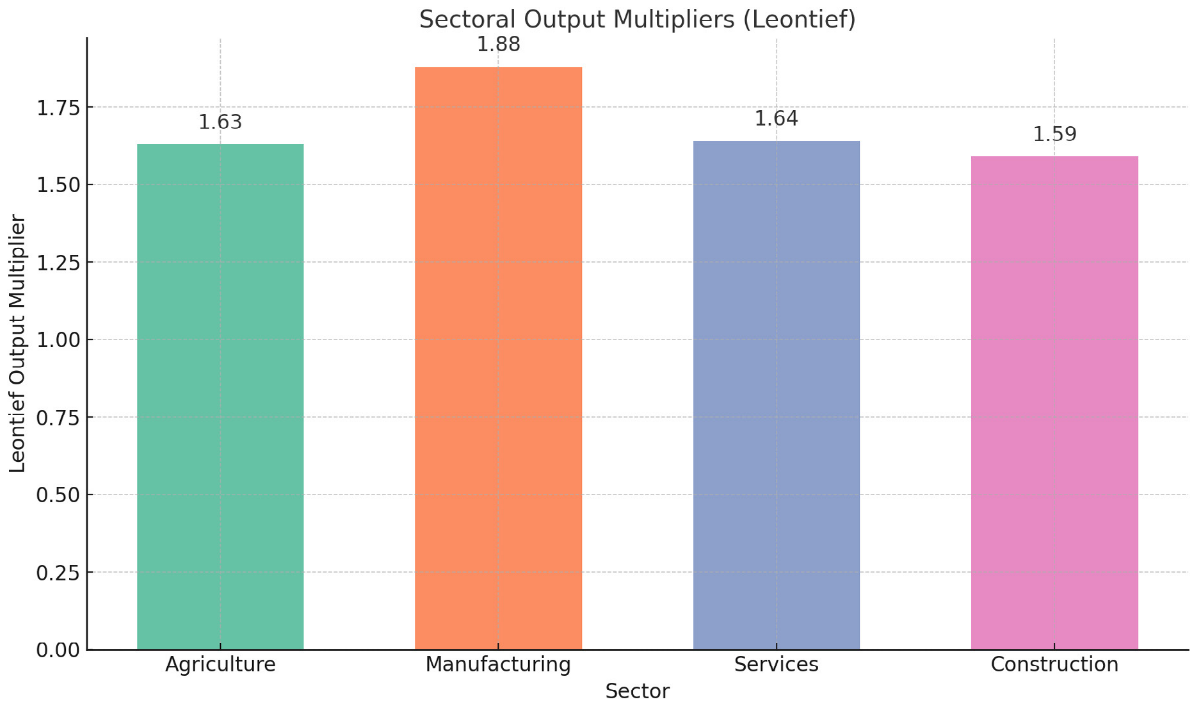



**Figure.5** *Sectoral output multipliers ( leontief)*
*Source: Author's simulation based on 2023 EE-SAM*

Figure (06) presents the sectoral output multipliers based on the 2023 Algerian Input-Output Table. The manufacturing sector registers the highest multiplier (1.88), followed by agriculture (1.63). These values indicate that a 1 DZD increase in final demand generates 1.88 DZD in total output for manufacturing and 1.63 DZD for agriculture. The strong multiplier in manufacturing is partly driven by the inclusion of the desalination sector, which is capital- and energy-intensive and involves upstream linkages with energy, infrastructure, and service sectors. This relationship explains the observed increase in manufacturing output in Scenarios 2 and 3, as water reallocation and capacity expansion necessitate higher desalination activity. The growth in desalination thus indirectly amplifies manufacturing sector output through investment and operational flows.

On the agricultural side, the high multiplier reflects robust linkages with local supply chains such as fertilizers, labor, transport, and agri-services. The results imply that redirecting or expanding desalinated water supply for agriculture (especially in Scenario 3) can yield substantial economy-wide benefits, supporting job creation, rural development, and food security without compromising industrial gains. These findings underscore the complementary, rather than competing, nature of strategic water allocation.

## DISCUSSION AND POLICY IMPLICATIONS

The results from the CGE-consistent simulations indicate that reallocating a portion of desalinated water from urban to agricultural use leads to notable economic and social benefits, with manageable environmental trade-offs. Table (06) summarizes the main results.

| Criteria | Scenario 1: Urban-only Use | Scenario 2: Reallocation to Agriculture | Scenario 3: Expanded Capacity for Agriculture |
|---|---|---|---|
| **Water Allocation Logic** | Desalinated water used exclusively for urban and service sectors | Partial reallocation from urban use to agriculture | Additional desalinated water (10%) allocated to agriculture without reducing urban supply |
| **Economic Output** | Baseline | Moderate increase due to agriculture and manufacturing gains | Stronger gains, especially in agriculture |
| **Value Added (GDP Proxy)** | Lowest value added | Improved value added from agriculture | Highest value added across sectors |
| **Labor Income** | Lower job creation and income impact | Increased employment in agriculture | Highest employment and income effects |
| **Manufacturing Impact** | Stable (reference point) | Moderate gains due to desalination input | Output unchanged; more gains shift to agriculture |
| **Environmental Impact** | Lowest brine and emissions levels | Higher brine and $CO_2$ due to increased desalination use | Highest brine, energy consumption and emissions due to new capacity |
| **Distributional Effects** | Urban households benefit more | Improved income for rural/agricultural households | Broad-based household gains |
| **Infrastructure Stress** | No trade-offs | Urban supply reduced – potential stress if demand increases | Avoids stress on urban systems but raises environmental risks |
| **Policy Feasibility** | Politically feasible but economically limited | Trade-offs may be controversial | Aligns with Algeria's national strategy (Reuters, 2024); feasible with adequate safeguards |
| **Sustainability Trade-offs** | Water security prioritized | Economic-environmental tension due to diversion | Balanced gains but requires mitigation of environmental externalities |
| **Best Fit (Time Horizon)** | Short-term fix | Medium-term productivity shift | Long-term strategy for resilient agriculture and food security |

**TABLE 6**
**Results Summary**
*Source: Source: by the authors*

The results of the CGE simulations highlight the complex balance between economic growth, social inclusion, and environmental sustainability when reallocating or expanding desalinated water use in Algeria. Economically, Scenario 3 delivers the strongest performance, increasing total output and value added more significantly than Scenarios 1 and 2. This is due to its design as a no-compromise solution: it expands desalination capacity without diverting water from urban uses, allowing the agricultural sector to grow without penalizing others. Scenario 2, though more modest, still yields notable GDP and labor income gains through internal reallocation. Scenario 1, reflecting the current status quo, maintains macroeconomic stability but underutilizes water as a lever for economic transformation.

From a social perspective, Scenario 3 also offers the most inclusive benefits. By channeling water to agriculture — a labor-intensive sector — it generates the highest increase in labor income and rural employment. This supports SDG 8.5 (inclusive growth and employment) and SDG 10.1 (income growth for the bottom 40%). Scenario 2 also boosts employment but raises concerns about potential water stress for urban areas, especially since Algeria's current desalinated supply does not fully meet municipal demand. Scenario 1 shows limited contribution to job creation, reflecting the capital- and energy-intensive structure of current desalination systems.

Environmentally, however, Scenario 3 presents the highest trade-offs. Brine discharge increases by 30% compared to Scenario 1, and energy use also rises significantly. While the CGE model integrates some of these effects through the environmentally extended SAM — including brine volume and energy consumption — several other externalities are not internalized. These include the ecological impacts of marine water intake, cumulative effects on coastal ecosystems, noise pollution from high-pressure pumps, and the economic burden of distribution infrastructure (Plan Bleu, 2024). This underlines the need for additional environmental modeling or ex-ante impact assessments to guide policy.

In terms of SDG alignment, Scenario 3 supports:

- SDG 2.3: Enhancing agricultural productivity and incomes.
- SDG 6.4: Improving water-use efficiency through strategic reallocation.
- SDG 13.2: Strengthening climate resilience in water and agriculture.
- SDG 8.5: Boosting inclusive and sustainable employment.

However, it may risk undermining SDG 12 (sustainable production) and SDG 14.1 (marine pollution) unless environmental safeguards and renewable energy sources are integrated into desalination expansion efforts (Abdelbaki et al., 2024).

The Spanish experience provides useful insights. In arid regions such as Murcia and Almería, Spain has used desalination to stabilize agricultural output under water stress. However, studies have flagged challenges, including energy dependency, high unit costs, and marine ecosystem risks due to brine disposal (Martín-Gorriz et al., 2020; Pérez & Martín-Gorriz, 2021). Spain has partially mitigated these effects by subsidizing desalinated water, introducing brine management protocols, and linking desalination to renewable energy projects — strategies Algeria could consider as it scales up.

In conclusion, no single scenario offers a perfect solution:

- Scenario 1 is low-risk but misses development opportunities.
- Scenario 2 is realistic but may exacerbate urban stress.
- Scenario 3 is transformative, economically and socially, but requires serious attention to environmental costs and technical feasibility.

This complexity reinforces the need for phased implementation, multi-criteria planning, and policy integration across water, energy, and agriculture sectors. Desalinated water can be a pillar of Algeria's food security strategy, but only if paired with technological innovation and robust environmental governance.

**Policy implication:**

To guide Algeria's transition toward a more resilient, inclusive, and sustainable water–agriculture system, the following recommendations are proposed. They are structured around four strategic dimensions — economic, environmental, social, and cross-cutting governance — and directly informed by the results of the CGE simulations.

**Economic Dimension**

- Establish a Targeted Subsidy Scheme for Agricultural Desalinated Water Use :

Given the high production and distribution costs of desalinated water, the government should consider smart subsidy mechanisms to make its agricultural use financially viable — especially in regions with high economic return per cubic meter of water. These schemes should be conditional, performance-based, and informed by cost–benefit analyses comparing desalination to alternatives like treated wastewater.

- Prioritize Investment in Inland Water Conveyance Infrastructure

Transporting desalinated water from coastal plants to inland agricultural zones (notably Tlemcen and Mascara) requires robust pipeline and pumping infrastructure. Prioritizing such investments, possibly through public-private partnerships (PPPs), is critical to scaling Scenario 3 in a financially and logistically feasible manner.

**Environmental Dimension**

- Mandate Environmental Impact Assessments (EIA) Prior to Scaling Desalination Projects

Before any scale-up of desalination for agricultural use, comprehensive EIAs should be conducted — accounting not only for brine discharge but also for marine water intake effects, energy use, and cumulative ecosystem impacts. This aligns with best practices observed in Spain's coastal regions (Martín-Gorriz et al., 2020).

- Promote Renewable-Powered Desalination Facilities

To limit the carbon footprint and energy intensity of desalination (particularly under Scenario 3), Algeria should invest in hybrid desalination technologies powered by solar or wind energy. This would reduce dependence on fossil fuels and support SDG 7.2 and 13.2.

- Develop and Enforce Brine Management Protocols

Clear environmental regulations for brine disposal must be introduced and enforced, including location-specific thresholds and treatment technologies to protect marine ecosystems from salinity and temperature shocks (Pérez & Martín-Gorriz, 2021).

**Social Dimension**

- Design Inclusive Agricultural Support Programs

Redirected water flows to agriculture (Scenario 2 and 3) generate significant employment, particularly in rural areas. The government should leverage this opportunity by developing support programs for smallholder farmers, including microcredit schemes, affordable drip irrigation technologies, and targeted training.

**Cross-Cutting Recommendations**

- Institutionalize the Use of CGE and Integrated Modelling in Water Policy

To ensure evidence-based planning, Algerian institutions should adopt Computable General Equilibrium (CGE) models extended with environmental accounts as standard tools for evaluating water policies. These models allow simulation of economic, social, and ecological trade-offs, offering valuable foresight for scaling desalination while managing environmental risks and distributional impacts.

- Develop a National Roadmap for Strategic Water Allocation

Algeria needs a long-term roadmap that integrates desalination, wastewater reuse, and groundwater sustainability under a unified framework. This roadmap should prioritize regions and sectors based on water productivity, economic spillovers, and SDG contributions.

## CONCLUSION

This study employed a Computable General Equilibrium (CGE) model based on an Environmentally Extended Social Accounting Matrix (EE-SAM) to evaluate the economic, social, and environmental implications of reallocating and expanding desalinated water use in Algeria. Three distinct scenarios were analyzed, reflecting the current state (Scenario 1), internal reallocation to agriculture (Scenario 2), and expanded production for multi-sectoral use (Scenario 3).

The findings confirm that desalinated water can be a powerful lever for economic transformation when integrated into agriculture — a sector with high employment intensity and domestic linkages. Scenario 3 consistently demonstrates the highest economic and social returns, while Scenario 2 offers a pragmatic compromise that leverages existing capacity with moderate gains. Scenario 1, while stable, reveals the underutilization of desalinated water as a development instrument.

However, these benefits are not without costs. Scenario 3, in particular, generates significant environmental pressures, including higher brine discharge and energy consumption. These trade-offs highlight the urgent need for environmental safeguards and integrated planning frameworks that span the water–energy–agriculture nexus.

From a policy perspective, no single scenario is universally optimal across time horizons:

- Scenario 1 is best suited for short-term stability, maintaining service continuity while preparing reforms.
- Scenario 2 aligns with a medium-term transition, optimizing current infrastructure while gradually expanding agricultural capacity.
- Scenario 3 is a long-term development strategy, unlocking transformative gains but requiring substantial investment, governance, and environmental risk mitigation.

Ultimately, the pathway forward should not rely on a singular solution, but on a phased, adaptive approach that balances growth, equity, and sustainability. Coupling desalination with strategic agricultural use supported by renewable energy, inclusive policy, and robust environmental monitoring — can serve as a cornerstone of Algeria's food security and climate resilience strategy, in line with SDGs 2, 6, 8, 13, and 14.

**Limitations and Future Research**

This study provides a macroeconomic and environmental assessment of desalination scenarios using a CGE model, but it does not capture all technological and ecological nuances. Key limitations include the exclusion of detailed plant-level technologies, spatial variability in environmental impacts (e.g., marine ecosystems, noise), and the economic cost of water distribution infrastructure (Plan Bleu, 2024). Behavioral responses and institutional constraints are also abstracted.

Future research should incorporate spatial and technical differentiation, as well as micro-level dynamics, to better inform investment and policy design.

# CHAPTER III. REGULATORY ASPECTS AND PUBLIC POLICY RELATED TO WATER MANAGEMENT


## Chapter III Introduction

Regulatory frameworks are central to achieving sustainability in unconventional water activities. These should be adapted to sector specificities with a holistic water management vision, applicable from national to local scales.

This chapter analyzes how the desalination sector aligns with Mediterranean regulatory frameworks, with particular focus on synergies and gaps within spatial planning regulations. The analysis focuses on Algeria as a case study, examining the extent to which desalination is integrated into Algerian water resource management legislation. The first paper provides a wider comparative analysis with global regulatory frameworks, particularly the Barcelona Convention and its eight Protocols on Integrated Coastal Zone Management. It proposes tailored operational recommendations to optimize sustainable deployment and operation of desalination facilities within Algeria's national water management framework.

The second paper adopts a more quantitative approach, analyzing potential impacts on water management when unconventional water resources such as desalination and wastewater treatment are integrated at provincial scales. This study examines how Algerian water management systems might be transformed by 2050, considering water stress, demographic patterns, and hydrological changes, thereby identifying strategic opportunities for more efficient national water resource management.

These complementary studies bridge the gap between regulatory theory and practical implementation, providing both the institutional framework and the quantitative projections needed for evidence-based water policy decisions. Together, they demonstrate how solid regulatory foundations can facilitate the strategic integration of unconventional water resources into national water management systems.

# GOVERNANCE AND EXECUTIVE REGULATORY TOOLS FOR A MORE SUSTAINABLE DESALINATION INDUSTRY IN ALGERIA

AUTHOR : NAJET AROUA

Desalination site © Poco_bw


## Abstract

This paper provides a comprehensive analysis of the governance mechanisms and regulatory frameworks surrounding seawater desalination in Algeria, within the broader context of coastal territorial development.

Faced with increasing water demand driven by urbanization, industrialization, and climate change, Algeria has heavily invested in non-conventional resources. Since 1995, the National Water Plan has prioritized seawater desalination to alleviate pressure on conventional sources and ensure reliable water supply to coastal cities. The current National Water Strategy aims to expand desalination capacity to 3 million m³/day by 2030.

However, the paper argues that the proliferation of desalination plants may create a false sense of water security. While desalination offers immediate relief, it is energy-intensive, costly, and has limited operational lifespans. Moreover, its expansion could accelerate coastal urbanization, increasing water demand and pressure on fragile ecosystems.

The study aims to critically examine the territorial coherence of seawater desalination plants (SWDPs) by assessing their alignment with:

i) local potable water needs, in light of available conventional resources and municipal demand;

ii) the national coastal development strategy, considering spatial planning and sustainable development goals;
iii) principles of Integrated Coastal Zone Management (ICZM), as defined in Protocol 8 of the Barcelona Convention.

The methodology combines:

i) a spatial analysis of existing and planned SWDPs along the Algerian coast, integrating geo-location, production capacity, technology, and commissioning dates;

ii) a qualitative assessment of territorial coherence based on three criteria:
1. Potable water demand vs. supply: SWDPs should be located where water demand exceeds the availability of conventional resources.
2. Coastal development strategy: SWDP deployment should align with land-use planning and promote energy-efficient, sustainable growth.
3. Barcelona Convention principles: Projects should support climate adaptation and environmental protection, in line with ICZM.

The analysis reveals that the deployment of seawater desalination plants in Algeria follows a territorial logic aligned with regional water deficits, particularly in the western coastal wilayas. However, their long-term contribution to water security remains constrained by environmental impacts, limited cross-sectoral coordination, and fragmented spatial planning.

The study underscores the need to reposition desalination within a broader, more integrated vision—by reinforcing anticipatory governance, integrating SWDPs into territorial planning instruments, and enhancing environmental monitoring to ensure alignment with sustainable development and ICZM principles.

Recommendations provide actionable guidance to improve governance and regulatory coherence, supporting governmental agencies, policymakers, and international organizations such as Plan Bleu in advancing more sustainable, climate-resilient coastal management.

**Keywords:** Algeria, Integrated Coastal Zone Management, Seawater desalination plant, Territorial balance and sustainability, Water security

## INTRODUCTION

### *Hydrological context in Algeria*

This The geography of Algeria is characterized by significant variations in topography, climate, and aquifer reserves. As shown in Fig. 1, these factors divide the territory into three bioclimatic zones with differing agricultural potential: Mediterranean, semi-arid, and arid. Population and economic activities concentrate mainly in the northern and especially eastern regions, where conditions are more favorable.

The country's main water resources are located in the four northern hydrographic basins, but decline markedly from east to west (Fig. 2). Fig. 3 shows an average one-third reduction in per capita water allocation (m³/capita/day) for the 2020–2030 period. Algeria faces a structural hydrological deficit, most acute in the western regions. The water stress index rose from 126% in 2015 to 138% (FAO & UN-Water, 2024).

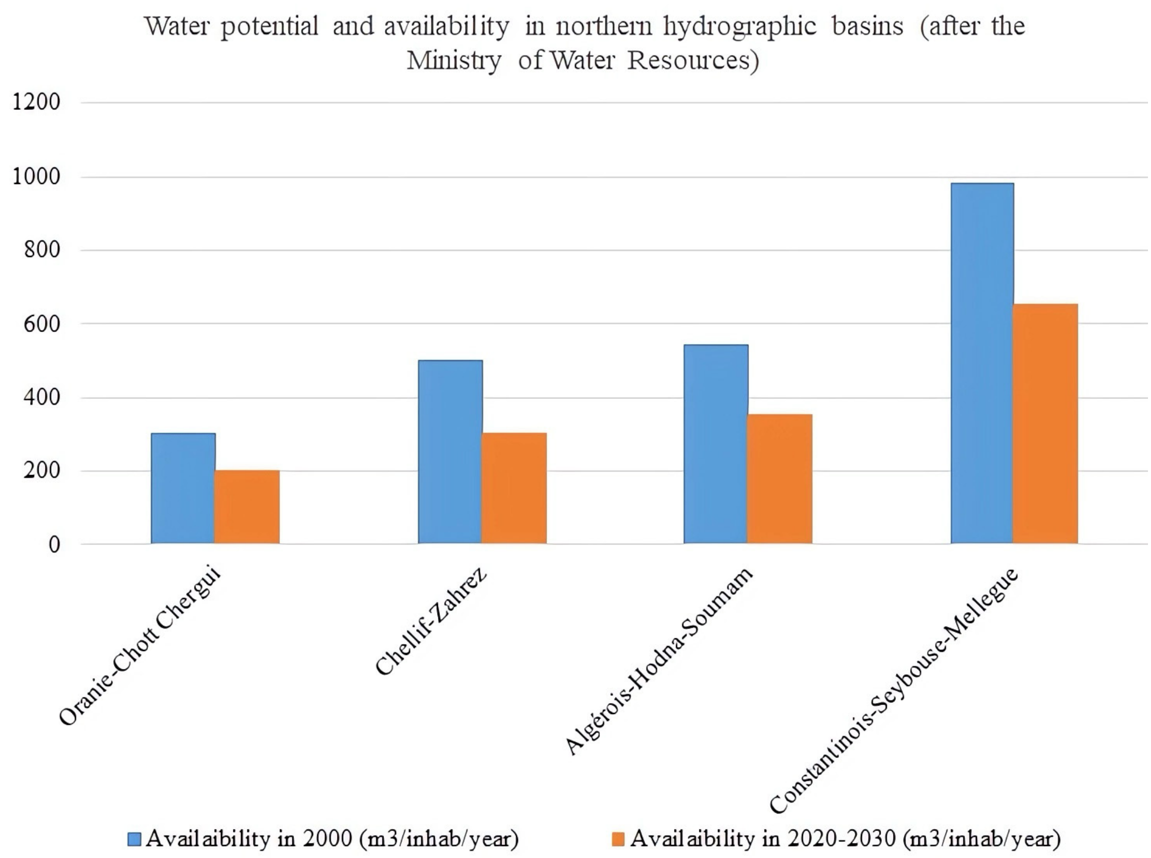



**Figure.1** *Water availability within Algeria northern hydrographic regions (ANRH, 2004)*

A predominantly arid climate, a north–south gradient in water resource distribution, and growing anthropogenic pressure restrict annual availability to 420 $m^3$ per capita—well below the water scarcity (1,000 $m^3$) and water stress (500 $m^3$) thresholds (MRESH, 2020). This situation is mainly driven by demographic growth (≈2%/year), which increases water demand. The exploitation index, at 56% (MRESH, 2020), signals a foreseeable decline in per capita availability by 2030. Despite 98% average connectivity to the potable water network, only about 50% of actual needs are met, placing Algeria among countries experiencing extreme water stress (World Resources Institute, 2025).

The progressive depletion of renewable resources is aggravated by a nearly 100 km northward shift of the isohyet line. Climate projections indicate a 5–13% drop in precipitation and a temperature rise of 0.6–1.1°C by 2020 (Kara & Arif, 2009). This dynamic creates a dual challenge of rising demand and diminishing supply. According to SNAT 2030 diagnostic reports, Algeria is undergoing rapid urbanization (75%) alongside steady population growth (ONS, 2018).

To address this, the National Spatial Planning Scheme 2030 (SNAT) outlines strategic infrastructure initiatives: inter-basin transfers from the north to the High Plains, exploitation of the deep Albien aquifer for southern areas, and increasing reliance on seawater desalination to meet coastal water needs (Law 10-02, June 29, 2010). The National Water Strategy aims to scale up desalination to 3 million $m^3$/day by 2030 (MRESH, 2020).

## *Increasing pressures on water resources and strategy for dealing with water deficit in the coastal zone*

In the context of seawater desalination, the study is geographically anchored in the coastal zone, where such infrastructure is inherently situated due to proximity to marine resources and its strategic relevance for territorial development.

Algeria's 2,148 km-long coastal zone includes 3,929 $km^2$ of land and 27,998 $km^2$ of marine area, with coastal plains, forests, wetlands, cultural heritage sites, islands, and the territorial sea. It hosts around 71 protected areas of ecological value. Characterized by rocky and sandy shores, this fragile zone is under intense pressure from urbanization and natural hazards like erosion and marine flooding (Mezouar, 2022).

The Coastal Action Plan for Algiers, Oran, and Annaba promotes sustainable urban growth, integrated water and solid waste management, and the protection of natural and cultural heritage (Ministry of Environment, 2025). The delineation of coastal zones—spanning 3 to 5 km—aims to control urbanization and prevent further degradation of ecosystems and marine biodiversity.

Natural conditions show a west-to-east gradient in rainfall, from ~400 mm in the west to ~900 mm in the east (Ministry of Water Resources). Despite this, a rainfall deficit of 20–25% in the west and 10–15% in the east persists (Ministry of Environment & GIZ, 2019). In light of a projected coastal population of 15.5 million in 2020 (ONS), annual water needs were estimated at 6525 $Hm^3$, exceeding the availability in many sub-basins. Water stress and drought levels are highest in the west, moderate in the center, and lower in the east.

Coastal wilayas face growing governance, land-use, and climate change challenges (Ministry of Environment, 2015). The SNAT 2030 recommends redistributing the population inland, establishing marine parks, and scaling up non-conventional water resources, including seawater desalination, which, though costly, has become strategic for drinking water supply in coastal cities.

These pressures contribute to the fragmentation of agricultural land and increased ecosystem fragility. While demographic growth persisted until 2008, it has since slowed down, though remains high in urban hubs like Oran, Algiers, Skikda, and Annaba (ONS, 2015; Ministry of Environment & GIZ, 2019).

The National Spatial Planning Scheme highlights the dual issues of water depletion and unsustainable urbanization, fueling rural-to-urban migration and unchecked coastal expansion. According to the National Coastal Authority (CNL, 2017), further environmental threats stem from unregulated tourism, deficient waste management, and the discharge of untreated wastewater, undermining the long-term resilience of coastal systems.

## *Desalination as a strategic response*

In response to escalating water demand—projected to reach nearly 200 million $m^3$/year by 2030 (MRESH)—Algeria's water policy has historically prioritized structural interventions and large-scale hydraulic infrastructure. However, this supply-driven approach has proven suboptimal in addressing needs in potable water supply, sanitation, and irrigation, despite significant financial investments. Water use efficiency, currently 61.7%, is expected to reach 75% by 2030 (Benblidia, 2011).

The current strategy shifts focus to institutional reform, climate adaptation, and enhanced resource mobilization, particularly through non-conventional sources. Among them, seawater desalination has emerged as a strategic solution, especially for coastal cities in water-stressed western regions. The government plans to expand desalination infrastructure along the coastline, distributing desalinated water over 100–150 km, with a goal to meet 50% of national water demand by 2030 (MRESH, 2020).

According to MRESH and Plan Bleu, approximately 48 desalination plants (SWDPs) are operational as synthesized on Table 1[11]. Most are located in the western hydrographic regions (Oranie-Chott Chergui and Chelif-Zahrez), where water availability is lowest. These plants, predominantly medium-sized, produce 10–200 MGD and supply municipalities with potable and ultra-pure water in line with WHO TDS standards. Their physical footprint, production capacity, and distribution distance—which can extend up to 150 km—significantly affect cost, depending on terrain, infrastructure, technology, and demand levels (UNDP, 2020).

While desalination addresses water scarcity, it generates environmental externalities impacting marine and terrestrial ecosystems and altering coastal morphology. Algeria's coastline is already affected by erosion, subsidence, and sea level rise—projected at 20 cm by 2030—leading to shoreline retreat and increased saltwater intrusion, especially due to overexploitation of coastal aquifers (Ministry of Environment & GIZ, 2019; Lakehal, 2023).

As shown on Fig.2. most SWDPs are found in the west (70%), within the two hydrographic regions of Oranie-Chott Chergui and Chelif-Zahrez), where water availability is the lowest, compared to 20% in the central region and 10% in the eastern region (Lakehal, 2023). However, a great number of existing SWDPs benefit Algiers, the capital city. According to their online dates, they were also the first to be built. However, a detailed analysis may reveal variability in their service timelines depending on plant size and maintenance quality. Their service lifespan is estimated at 25 years, but variation depends on plant size and maintenance quality. Beyond this period, new infrastructure will be needed unless less environmentally impactful alternatives are implemented.

The National Water Strategy targets a desalination capacity of 3 million m³/day by 2030 to secure urban water supply, reduce pressure on groundwater, and enhance rainwater harvesting and wastewater reuse. As of 2025, desalinated water will meet up to 42% of demand in five coastal wilayas (Oran, Tipaza, Boumerdes, Béjaïa, El Tarf), with several nearly completed plants each producing 300,000 m³/day. A complementary program includes six mega-projects totaling 1.8 million m³/day. Desalination is thus framed as a strategic, long-term solution, with future plants planned to be powered 30–40% by solar energy. Overall, production is projected to increase by 46.6% between 2025 and 2030 (from 3.75 to 5.5 million m³/day)[12].

## *Issue, main objective, specific objectives*

Despite the growing body of literature on desalination, most research remains centered on technical dimensions—such as process optimization, infrastructure design, and energy efficiency—and environmental impacts, particularly saline discharges and marine ecosystem degradation (Williams, 2022). These studies aim to improve desalination performance, materials, and cost-effectiveness. However, they often lack an integrated, long-term perspective that combines socio-economic, environmental, and territorial variables.

Crucial factors such as demographic trends (population growth and spatial distribution), climate-related pressures (declining precipitation, sea level rise), the geographic optimization of plant locations, the adaptation of production capacities, and the lifespan extension of infrastructure are rarely addressed in a cross-sectoral and spatialized manner. Yet, desalination infrastructure deployment must be assessed not only through technical and resource-based lenses but also in relation to urbanization patterns, territorial coherence, and the principles of Integrated Coastal Zone Management (ICZM).

This paper posits that the integration of desalination plants into Algeria's coastal zones must be framed within a territorial planning paradigm that safeguards sensitive coastal ecosystems, biodiversity hotspots, and areas vulnerable to climate change. Moreover, plant development and operation must align with the Barcelona Convention and its protocols—particularly Protocol 8 on ICZM—ensuring that urban growth and economic development do not undermine natural resource conservation or ecosystem resilience.

An important hypothesis explored in this study is that the proliferation of desalination plants may generate a false sense of water security. While these infrastructures offer essential relief in water-stressed areas, their energy intensity, finite lifespans, and cost-benefit uncertainties raise concerns about long-term economic, environmental, and social viability, especially in the context of coastal demographic pressures. Furthermore, increased desalination capacity may unin-

11 This figure only accounts for desalination plants currently in operation and is likely to rise, as additional facilities either are under construction or scheduled for implementation in the near future

12 Bada L. (2025, 06 janvier), L'Algérie est un acteur majeur dans l'industrie du dessalement d'eau de mer, El-Watan, p.2. Interview by Iddir N.

tentionally encourage coastal urban expansion, exacerbating water demand and further stressing fragile ecosystems.

Accordingly, this paper aims to provide a critical territorial analysis of Algeria's seawater desalination plant (SWDP) network by evaluating its alignment with three key dimensions:

1. Local potable water needs, based on the availability of conventional water resources in coastal watersheds and the per capita demand of recipient municipalities;
2. The coastal development strategy, through the lens of spatial planning regulations within sustainable development and climate change adaptation frameworks;
3. The principles of Integrated Coastal Zone Management (ICZM), as outlined in Protocol 8 of the Barcelona Convention.

## METHODOLOGY

### *Analytical approach*

The analytical approach adopted in this study combines a literature review, a case study analysis, and a spatial assessment to evaluate the territorial coherence of seawater desalination plants (SWDPs) in Algeria.

The literature review encompasses scholarly and technical works on desalination technologies, integrated water resources management, climate change impacts on water availability, and territorial dynamics of coastal zones. It also incorporates Algerian strategic, regulatory, and executive planning documents with a 2030 horizon, along with international commitments, notably the Barcelona Convention and the Mediterranean Strategy for Sustainable Development.

Empirical data collection focuses on four coastal municipalities—Tlemcen, Oran, Algiers, and Skikda—selected for their significant number of desalination units (respectively 4, 9, 13, and 6), their hydro-climatic diversity, and their varying urban growth trajectories. These municipalities serve as demonstrative case studies representative of Algeria's western, central, and eastern coastal regions. Complementary insights are drawn from informal interviews with stakeholders and public discourses, while cartographic data support the spatial analysis of SWDP distribution, urban proximity, and associated environmental impacts.

The analysis consists of:

1. A spatial assessment of existing SWDPs, integrating geo-location, production capacities, technologies, commissioning dates, and cartographic representation (see Table 4).
2. A qualitative territorial coherence analysis, based on three interrelated criteria:

i) Per capita drinking water requirements: This dimension cross-references the daily production capacity of SWDPs with national standards for per capita drinking water needs (see Table 5), calculated for the 2020 population and 2030 projections. The availability of conventional water resources at the coastal watershed level serves as a key qualitative indicator, given that SWDPs are designed to supply areas with water deficits.
ii) Alignment with the national coastal protection and valorization strategy: This criterion assesses whether SWDP distribution supports national sustainable development goals and coastal zone regulations, particularly by enhancing water security, optimizing energy use, and respecting land-use planning frameworks. The qualitative indicators used include energy accessibility and land-use compatibility.
iii) Compliance with international ICZM principles: This analysis examines the spatial distribution of SWDPs against the principles of Integrated Coastal Zone Management (ICZM) as defined in Protocol 8 of the Barcelona Convention. The key criterion is the alignment of SWDP deployment with environmental protection, climate change adaptation, and mitigation objectives.

### *Conceptual frameworks*

This study is grounded in a three-pillar conceptual framework that integrates the notions of water security, Integrated Coastal Zone Management (ICZM), and the geography of seawater desalination plants (SWDPs). Together, these interrelated dimensions provide a comprehensive lens for assessing the territorial sustainability of Algeria's desalination strategy and its consistency with international commitments, notably the Barcelona Convention and its protocols.

- Water Security[13]: The concept of water security is operationalized through ten key criteria: availability, accessibility, quality, affordability, reliability and continuity, risk management, governance, and institutional capacity. Each criterion is scored on a 10-point scale, and the national water security score is derived from

13 The UN-Water defines water security as being "the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socioeconomic development, for ensuring protection against waterborne pollution and water related disasters, and for preserving ecosystems in a climate of peace and political stability" (UN-Water, 2023). Two main assessment approaches have been proceeded: i) Multi-criteria analysis based on quantitative indicators (e.g. m³ of water per capita/year, frequency of supply interruptions, % of population with access to improved water sources) and qualitative indicators (e.g. perception of water quality, stakeholder satisfaction) and ii) Risk-Based Assessment using risk matrices, scenario modeling, or hydrological modeling to evaluate exposure, vulnerability, and adaptive capacity to water-related risks. (UNU-INWEH (2013).

the aggregate. Based on this score, a country is classified as critical, insecure, moderately secure, or secure (UN-Water, 2023). This scoring system facilitates a multidimensional assessment of Algeria's water policy context.

- Integrated Coastal Zone Management (ICZM): ICZM promotes cross-sectoral coordination and long-term spatial planning to address the cumulative impacts of human activities, climate variability, and sea-level rise. It emphasizes the preservation of coastal biodiversity, natural resources, and livelihoods through integrated governance mechanisms that reconcile ecological integrity with socio-economic development.

- Geography of Seawater Desalination Plants (SWDPs): The spatial deployment of SWDPs involves complex site selection processes that must balance technical, environmental, economic, and social dimensions (UNDP, 2020). These are categorized into four main groups:

1. Technical feasibility: Proximity to the coastline (preferably within 1 km), land availability and constructability, and energy access.
2. Environmental considerations: Avoidance of sensitive or protected zones and hazard-prone areas (e.g., erosion, flooding, steep terrain).
3. Economic factors: Land cost and legal status, as well as transport distance to the target service area, with the goal of minimizing infrastructure and distribution costs.
4. Socio-economic aspects: Community acceptance, expected local benefits, and potential for conflict mitigation.

In accordance with international norms, each SWDP project must be accompanied by an Environmental Impact Assessment (EIA) to evaluate potential effects and mitigation strategies (UN-Water, 2020).

### *Governance framework related to the coastal zone management*

The Ministry of Environment and Quality of Life is the main body responsible for coastal zone management, assisted by other ministries (Fig. 3). A key regulatory institution, the National Coastal Council (CNL), was created in 2004 (Decree No. 04-113). Its mission is to implement protective and restorative measures, support local authorities, and promote public awareness (Art. 3).

Bay of Algiers © alanphillips

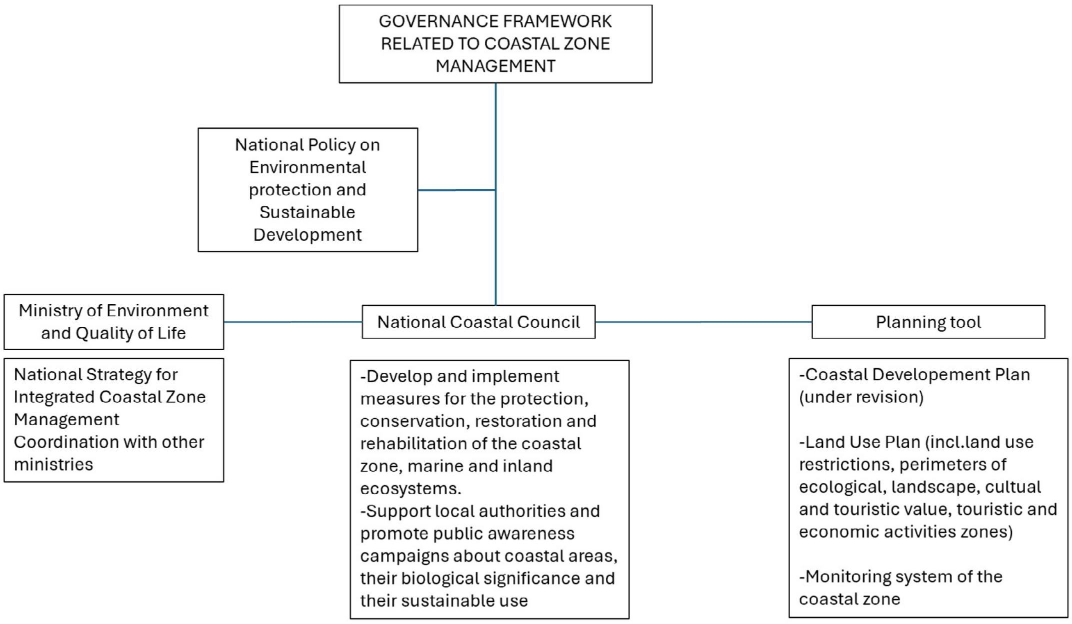



**Figure.2** *Governance framework of coastal zone management*

The steering committee, composed of ministry representatives and environmental associations, holds consultative authority over programs (Art. 7 and 8).

The CNL is the only body responsible for developing and implementing the national coastal strategy, framed by Law No. 2002-02 and its executive decrees, currently under revision[14]. This legal framework promotes sustainable development, prevention, and precaution (Art. 3), aligning with land use and environmental strategies[15].

Local authorities must limit urban sprawl, enforce non-aedificandi zones, and encourage relocation of polluting industries (Art. 4). The coastal zone encompasses a broad area, including islands, islets, coastal plains, wetlands, and sites of natural, cultural, or historical interest (Art. 7), imposing significant constraints on SWDPs siting and requiring compliance with integrated coastal zone management principles. Executive decrees detail land-use planning: preservation of natural balances (Art. 10), prohibition of activities in protected areas (Art. 11), urban expansion rules (Art. 12), siting of industries (Art. 15), and public infrastructure (Art. 16), with exceptions for strategic projects like SWDPs (Table 7).

The key planning instrument is the Coastal Master Plan, aligned with the National Spatial Development Master Plan. Though under revision, its core principles are reflected in the National Strategy for Integrated Coastal Zone Management 2030, which emphasizes monitoring, climate resilience, and integration with strategies on the blue economy, desalination, and tourism.

Decree No. 22-221 (2022) restricts tourism development on agricultural, forested, or protected lands (Art. 3). Decree No. 09-114 (2009) defines the Coastal Development Plan (CDP) as a tool aligned with higher-level plans, including technical diagnostics and management rules (Art. 2). So far, few wilayas have adopted a CDP—Algiers (2005), possibly Oran[16], and Béjaïa[17] (2024). Further analysis of the Coastal Master Plan (PAC) may clarify how SWDPs are spatially integrated and their environmental impacts addressed.

## *Governance framework related to the seawater desalination regulation*

The Ministry of Water Resources is the main institution involved in seawater desalination, with subsidiary involvement from other ministries as shown in Fig. 4. A specific regulatory body, the National Agency for Water Desalination (NAWD), was recently established (Executive Decree No. 23-103 of March 7, 2023). Its mission is to enhance national water production capacities to ensure long-term water security, ensure compliance with technical standards and regulations for desalination infrastructure, and coordinate with relevant institutions, notably in scientific research and industry (Chapter 2, Article 5).

13 For more information about the implementation of this law, see: Kacemi M. 2008. La Loi de protection et de valorisation du littoral en Algerie : Un cadre juridique ambitieux toujours en attente. Le cas du pôle industriel d'Arzew (Oran – Algérie), Proceedings of the international pluridisciplinary conference «The littoral : challenge, dialogue, action» - Lille, France, 16-18 january 2008, 11p.
15 This information is confirmed by both the CNL and the department responsible of the coastal zone in the Ministry of Environment and quality of life.
16 Kacemi (2011) refers to the document without supplying a corresponding bibliographic reference.
17 Décret exécutif n° 24-222 du 2 juillet 2024 portant adoption du plan d'aménagement côtier de la wilaya de Bejaya.

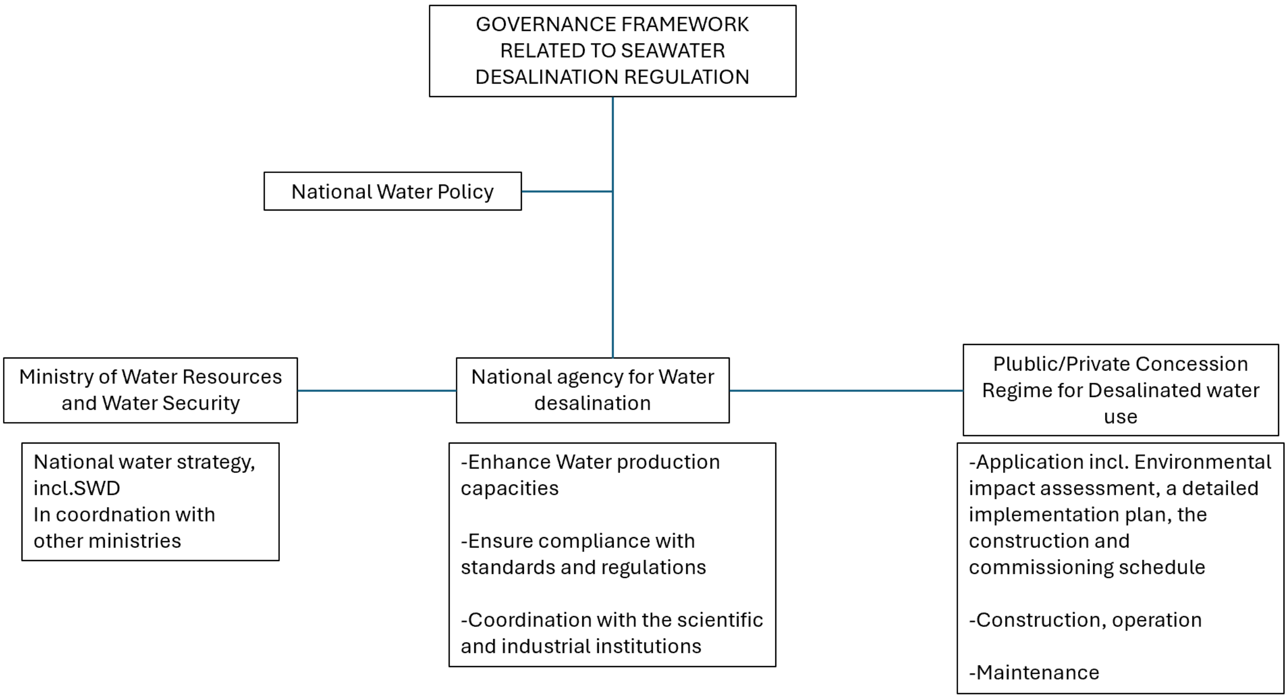



**Figure.3** *Governance framework of desalinated water in Algeria*

The NAWD is the first and only body responsible for developing and locally implementing the national desalination strategy. Its governing board, composed of representatives from key ministries (land use planning, energy, industry, environment, agriculture, health), holds decision-making authority for international cooperation and partnerships (Art.3 and 12).

Desalinated water use is governed by a concession regime (Executive Decree No. 11-220 of June 12, 2011), with applications submitted to the Ministry of Water Resources or the Wilaya Governor, depending on whether the project serves public utility or private purposes (Art.3). Applications must include geographical and technical details of the SWDP, cartography, and a Master Plan (1/500) (Art.4). Once accepted, the application is completed with an environmental impact assessment and implementation schedule (Art.7). Approval is formalized by a Ministry or Wilaya order specifying the site, production volume, use, and concession duration (Art.8-9). For public utility projects, the land is granted through a concession agreement and a specific executive decree (Annex, Chap.1, Art.1-5).

The concessionaire is responsible for construction, operation, maintenance, environmental measures, water quality checks, and liability for damages (Annex, Art.7, 12, 18). For example, Executive Decree No. 22-262 of July 6, 2022, regarding the Ain el-Karma SWDP (Wilaya of Oran), classified as public utility, allocates 74,402 m² for a capacity of 300,000 m³/day (Art.2), including supporting infrastructure (Art.3), with compensation provided by the Public Treasury in case of expropriation (Art.4).

# RESULTS

## *Case studies analysis*

### *Municipality of Tlemcen (Wilaya of Tlemcen)*

**General context:** The wilaya of Tlemcen (9017,69 km2) is located in the far west of Algeria, 34° 53' 24'' N and 1° 19' 12'' W. It has eight from fifty-three (08/53) coastal municipalities. The vocation of the wilaya is therefore mainly agricultural, somehow industrial, and touristic with regard to its significant cultural and natural heritage. The local climate is typically Mediterranean to semi-arid, defined by an average rainfall rate ranging from 200 to 500mm/year. In 2019, the population was 1 101 383 inhabitants Referring to the population growth rate of 2,05% , it is expected to be approximately 1,376,834 inhabitants in 2030 (according to the Wilaya of Tlemcen, 2025).

**Local water availabilities:** Local water availabilities are 209 Hm3. The wilaya is supplied by surface resources captured from surrounding mountains and hills, in addition to groundwater extracted from dozens well fields. The drinking water per capita allocation is 200 l/inhab/day in urban areas and 170 l/inhab/day in rural areas with a connection rate to the water supply network of 97% (according to the wilaya website).

**Water supply from SWDP:** As shown on Table 8, three among eight (3/8) coastal municipalities are supplied with drinking water from SWDP. The two first SWDPs sized M produce 5000 m3/d. They were built in 2003 and 2004 within the municipality of Ghazaouet, which is an important commercial and fishing port. Similarly, the municipality of Souk Tleta and the municipality of Honaine are supplied with drinking water (TDS 10ppm -<1000ppm) from two SWDP sized XL each, dating from 2010 and 2012 and producing 199 849 m3/d and 200 000 m3/d respectively. Souk Tleta is rather farming based, while Honaine is a fishing port and touristic seaside resort. Assuming a 25-year operational lifespan, Ghazaouet may continue to be supplied with desalinated water up to 2029, Souk Tleta and Honaine up to 2035 and 2037respectively. Namely, drinking water could be secured a couple of years more, whereas the population will continue growing at an average rate of 2,05% per year.

**Analysis of the Tlemcen case study:** As an example, according to the per capita national standards, drinking water total allocation for 6872 inhabitants living in Honaine in 2020, would have been 1 099,520 $m^3$/day. At that time, the SDWP, producing 200 000 m3/day, could theoretically have covered almost all local drinking water needs. In 2030, the percentage would remain the same despite the population increase (8418 inhab). The situation would be quite different in Souk Tleta hosting 3 516 in 2020, 4 302 by 2030. The per capita drinking water allocation is now 85 l/inhab/day in Souk Tleta. The XL SWDP, which appears to be able to cover the whole theoretical drinking water demand, will likely continue to do so up to 2035. As for Ghazaouet, the per capita drinking water allocation is now160 l/inhab/day. The percentage covered by desalinated water, which is now around 73% in Ghazaouet, will halt in 2029. An alternative should be found in 2030 and over.

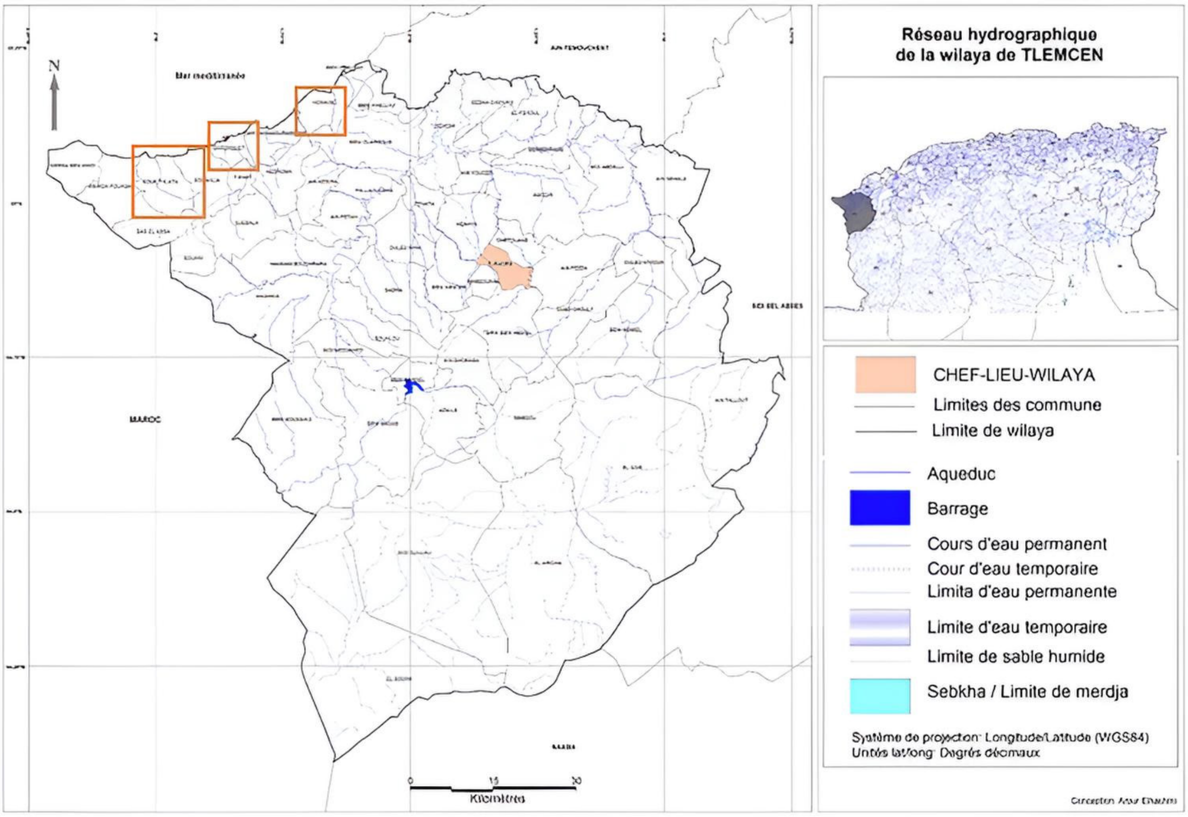



**Figure.4** *SWDP in coastal municipalities- Wilaya of Tlemcen (completed by the author using the base map of www.decoupageadministratifalgerie.com)*

Referring to the Master Plan for Tourism development in Algeria, the wilaya of Tlemcen is intensifying and diversifying its tourism products and multi-form services, with seaside being predominant, notably through high-standard tourist villages and seven Tourism Expansion Zones (SDAT, 2025). Furthermore, in 2019, there were around 48 housing programs, planned or in construction[18]. The urbanized area represented around 48% of the wilaya total surface resulting in 122 inhab/km2 (according to the Wilaya's official website). The wilaya is now classified as a low-density urban area (based on typical classifications derived from urban studies and density analyses, notably those inspired by UN-Habitat frameworks). That would explain the call for investment in various economic sectors, including tourism (ref. Carte territoriale des opportunités d'investissements dans la wilaya de Tlemcen).

## *The municipality of Oran (Wilaya of Oran)*

**General context:** The wilaya of Oran (1838,53 km2) is located in the west of Algeria, 35° 42' N and 0° 38' W. It has 14 from 26 coastal municipalities encompassing twenty protected areas, including marines. It is a hub for exchange, commerce, and tourism, with regard to its significant transport infrastructure (port, airport, rail and road network). The local climate is typically Mediterranean, whereas the average rainfall rate on average 450 mm/year defines a semi-arid climate (Sahabi, 2012).

In 2019, the population was 2 118 603 inhabitants. Referring to the population growth rate 3,18% , it is expected to be approximately 2,989,512 inhabitants in 2030[19].

**Local water availabilities:** Regarding the low local water resources, the wilaya is primarily supplied with water from the Chelif (110 million m3/year approximately) distant of 175 km and other dams providing 781,35 Hm3 as a total volume of surface water transferred, in addition to groundwater extracted from 1143 wells and desalination plants since 2002 (Bellal et al, 2015). The daily dotation is on average 170 l/inhab/day with a connection rate to the water supply network of 98%.

**Water supply from SWDP**: As shown on Table 9, two out of fourteen (02/14) coastal municipalities are supplied with drinking water from SWDP. The first SWDP was built in 2000 in the port municipality of Arzew, a major petrochemical complex benefiting from seven (07) SWDPs. Three out of seven supply the municipality with drinking water, while four produce ultra-pure water for industrial purposes. The municipality of Arzew is supplied with drinking water from three SDWP sized S, M and XL, with a total production capacity of 90 858 m3/d. The municipality of Bethioua is supplied with drinking water by SWDP sized M. Bethioua producing 5000 m³/d.

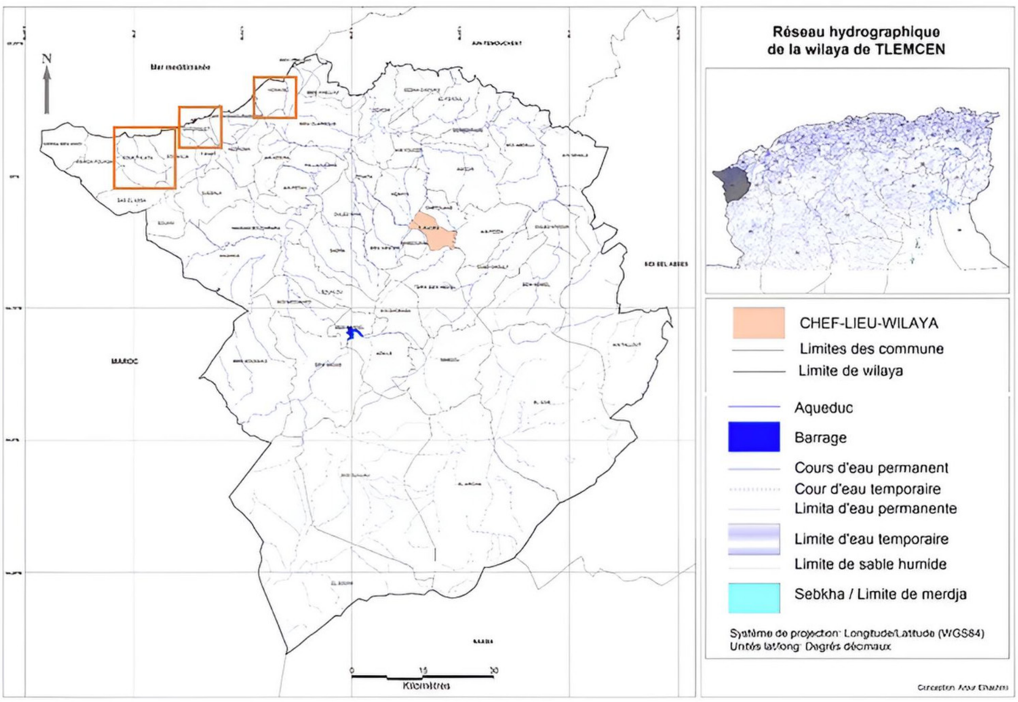



**Figure.5** *SWDP in coastal municipalities- Wilaya of Oran (completed by the author using the base map of www.decoupageadministratifalgerie.com)*

18 The Urban Development Master Plan of the coastal municipalities could provide insights into the current situation and planned projects (housing, public facilities, and infrastructure) within coastal areas. Unfortunately, this document could not be consulted for the purposes of this article.
19 After the website of the wilaya: https://wilayaoran.dz/

**Analysis of the Oran case study:** Assuming a 25-year operational lifespan, Arzew and Bethioua could continue to be supplied with desalinated water for a few more years. The population is expected to grow at an average annual rate of 3,18%, while the existing SWDPs are projected to cease producing drinking water between 2027 (earliest) and 2035 (latest). As an example, according to the national per capita standards - in this case 180l/inhab/d - , the total daily drinking water allocation for the 108 319 inhabitants of Arzew in 2020, would have been 19 497 m³/day. At that time, the three SDWP, could ideally have met the total need, as well as by 2030, despite the population growth (estimated at 117 509 inhabitants) and the reduction to two SWDP. The situation is quite similar in Bethioua, which had around 22 226 inhabitants in 2020 and is projected to reach 30 449 by 2030. Based on the per capita drinking water allocation – in this case 160 l/inhab/day - , the total daily drinking water needs amount to 4 001 m3/d in 2020 and 5 481 m3/d in 2030. The existing SWDP, which currently appears able to meet the entire theoretical demand, is likely to continue doing so until 2028. Beyond that date, an alternative solution will be required.

Referring to the Master Plan for Tourism development in Algeria, Oran remains attractive while it is a metropolitan strategic hub gathering four wilayates, Oran, Mostaganem, Sidi Bel-Abbas and Tlemcen (SNAT, 2030). It is also planned to further develop tourism through a high standing tourist village notably (SDAT, 2025). The urbanized area represented around 88% of the wilaya total surface with 1152 inhab/km2 in 2019 (according to the wilaya website). However fragmented and unequally developed as main residential, commercial and industrial areas concentrated in Oran and Arzew municipalities. The Urban master plan plans to remedy the situation by creating new housing and seaside touristic sites whereas the urban diagnosis reveals a damaged coastal area, exposed to the risks of high erosion and soil salinity (ANIREF, 2013). There is also a delineated preservation marine ecosystem around Oran which the Urban Master Plan recommended to protect through a rigorous implementation of the current regulations (Law n° 2002-02 dated 05/02/2002 related to the protection of the coastal area and associated executive decrees). The wilaya is classified as having medium population density (Based on typical classifications derived from urban studies and density analyses, notably those inspired by UN-Habitat frameworks). It is seeking investment in various economic sectors, including agriculture, industry and tourism (according to the website of Agence Algérienne de Promotion de l'Investissement, consulted on April 2025). Since the future closely depends on the present, it is worth mentioning a 2011 study that highlighted the lasting environmental impacts of the Ghazaouet industrial zone, involved in petrochemical activities (Kacemi, 2011). The author also raised the ineffectiveness of the Coastal Land-use Plan (Plan d'Aménagement Côtier), which despite identifying several sensitive natural areas of ecological interest, has not been able to prevent continued urbanization along the coast.

### *The municipality of Algiers (Wilaya of Algiers)*

**General context:** The wilaya of Algiers (1190 km2) is located in the central region of Algeria, 36° 42' N and 3° 13' E . It has 18 from 57 coastal municipalities. It is the state capital port-city and is therefore mainly dedicated to services, tourism in addition to being somehow agricultural and industrial. The local climate is typically Mediterranean, defined by an average rainfall rate ranging from 670 to 800 mm/year. In 2020, the population was 3 309 896 inhabitants.

**Local water availability:** Local water availability is 261 Hm3. The wilaya is supplied by surface resources and groundwater captured and extracted within coastal watersheds beyond its administrative boundaries. The daily dotation is on average150 l/inhab/day. It ranges from 100 to 180 l/inhab/d according to the number of inhabitants per municipality based on a connection rate to the water supply network of 98% (Ministry of Water Resources).

**Water supply from SWDP:** As shown on Table 1023, six out of eighteen (06/18) coastal municipalities are supplied with drinking water from SWDP. Assuming a 25-year operational lifespan, the Wilaya of Algiers' municipalities can continue to be supplied with desalinated water up to 2017 (earliest) and 2033 (latest), except that the municipality of Staouali wishes SWDP has been built more recently (in 2021). Drawing from existing SWDPs, drinking water could be secured a couple of years more, whereas the population will continue growing at an average rate of 1,6% per year. Analysis of the Algiers case study: As an example, the first SWDP sized M, was built in 2002 in the municipality of Ain Benian, an important seaside touristic place. Ain Benian is supplied with drinking water from two SWDPs sized M with a combined production capacity of 3 700 m3/d. As the population is expected to grow at an average annual rate of 1,6% and the national per capita standards - in this case 180 l/inhab/d - , the total daily drinking water allocation for the 75 739 inhabitants of Ain Benian in 2020, would have been 13 633 m³/d, around 15 955m3/d in 2030 (estimated pop= 88 764 inhab). At that time, the two SDWPs, could ideally have met around 27% need, 23% by 2030, with regard to the population growth.

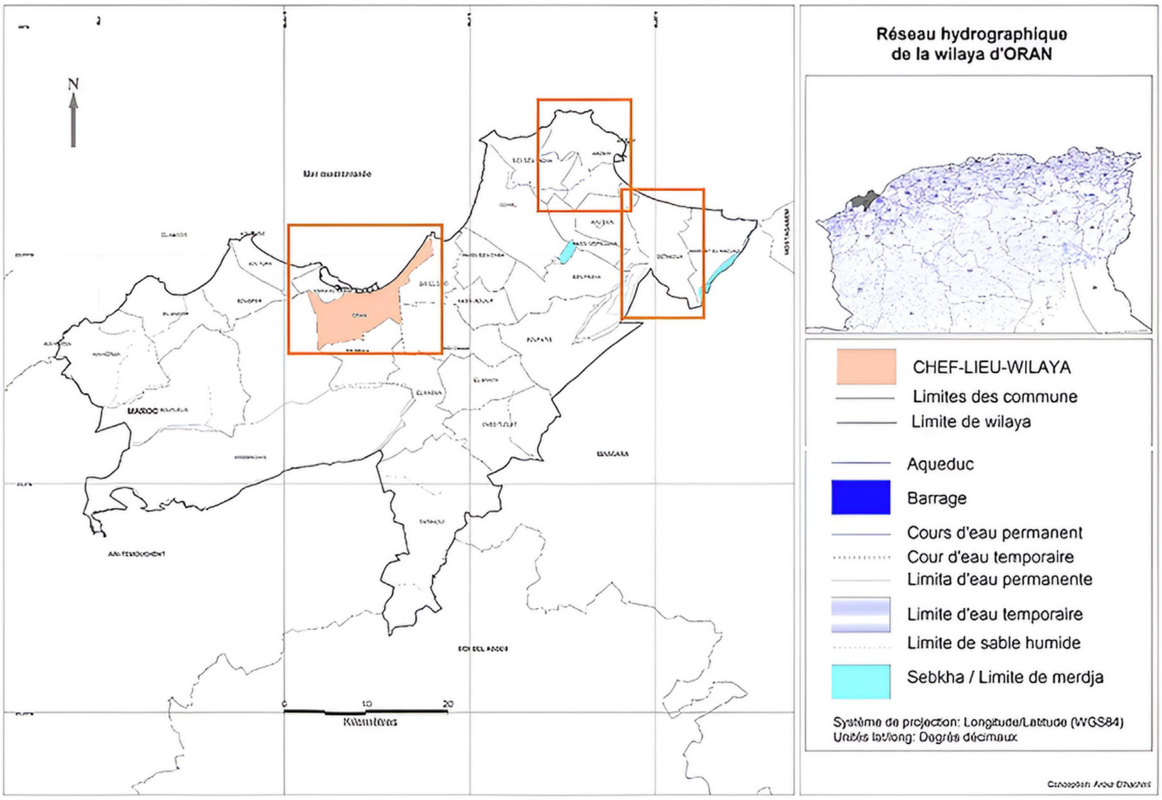



**Figure.6** *SWDP in coastal municipalities- Wilaya of Algiers (completed by the author using the base map of www.decoupageadministratifalgerie.com)*

Similarly, the total daily drinking water allocation for 94 685 inhabitants living in the municipality of Reghaia in 2020, would have been 17 043,3 m³/day. At that time, ideally, the SDWP, producing 10 000 m3/day, could have covered almost 59%. By 2030, this percentage would drop to approximately 50%, given the population growth. It is worth noticing that this percentage is an approximation, as the per capita allocation is a theoretical volume, quite different – and even higher- from the real consumption one. According to the Ministry, the satisfaction of water demand is closer to 50%.

The municipalities of Borj el-Kifan and Staouali could ideally meet around 15% and nearly 79% of their needs in 2020, 14% and 67 % respectively by 2030. The municipality of Hamma appears to be an exception, as the SWDP produces 200 000 m3/d for 75 206 inhabitants, with a total water allocation of 13 537 m3/d in 2020, and for a projected population of 88 130 inhabitants in 2030, with a total water allocation of 15 863 m3/d. In this case, it is important to note that the XL-SWDP located in Hamma, actually supplies several other municipalities within the Wilaya of Algiers. While it appears to be able to meet the municipality itself, at least up to 2033, the needs of neighboring districts and/or municipalities should also be considered. For instance, the municipalities surrounding Hamma are among the most densely populated in the wilaya.

Referring to the Master Plan for Tourism development in Algeria, the wilaya of Algiers is also intensifying and diversifying its tourism products and multi form services, with seaside tourism being the predominant, particularly through the development of high standing tourist villages (SDAT, 2025). The wilaya of Algiers, like the wilaya of Oran, remains attractive, while it is an expanding metropolitan strategic hub encompassing four wilayates, Algiers, Tipaza, Blida and Boumerdes (SNAT, 2030). Additionally, several housing programs are either planned or currently under construction within the wilaya of Algiers. The urbanized area represented approximately 80% of the wilaya total surface, resulting in a population density of 2759 inhab/km2 (website of the wilaya). Consequently, the wilaya is classified as a high-density urban area (Based on typical classifications derived from urban studies and density analyses, notably those inspired by UN-Habitat frameworks). As a capital-city, the wilaya is undergoing a number development projects, in addition to many others planned under the framework of the new Urban Master Plan. In particular, the housing program is continuing in order in response to the high demand, alas, often at the expense of the fertile lands of the famous Mitidja plain.

The Algiers Master Plan also includes provisions for the protection of the coastal area, along with its specific marine and coastal ecosystems, hydrosystems, biodiversity and wetlands (Ministère de l'environnement, 2006). At the same time, it aims to reconnect the city with the sea through prominent waterfront development projects. The law governing coastal area protection is being reviewed, likely due to that emblematic project and the planned seaside tourism zones, be it public or private. A key issue arises: how does the city intend to reconcile ecological and environmental requirements with this prestigious political and socio-economic vision, while providing water for all uses? Information regarding the planned or under-construction stations would have allowed us to address the question, at least partially. Unfortunately, it has not been communicated so far.

## *The municipality of Skikda (Wilaya of Skikda)*

**General context:** The wilaya of Skikda (4137,68 km2) is located in the far east of Algeria, 36° 45 N and 6° 49 60 E. It has eight from fifty-three (08/53) coastal municipalities. The vocation of the wilaya is mainly tourism and industry, specifically in the chemical and petrochemical sectors. The local climate is humid to sub-humid, typically Mediterranean, and defined by an average rainfall rate ranging from 1000 to 1500mm/year. It is actually among the wilayate with the highest annual rainfall in Algeria. In 2020, the population was 1 095 666 inhabitants Referring to the population growth rate 1,22% , it is expected to be approximately 1 295 000 inhabitants by 2030.

Local water availability: According to the national standards – in this case 180 l/hab/d - drinking water total allocation for 202 567 inhabitants living in the municipality of Skikda in 2020, would have been 36 462, 06 m³/day. At that time, the SDWPs with a combined production capacity of 119 000m3/day, may have covered almost all local needs in drinking water. In 2030, the percentage would remain the same despite the population increase (228 682 inhab).

Water supply from SWDP: As shown on Table 1124, only the municipality of Skikda, the chief-town of the wilaya, is supplied with drinking water from the SWDP. Assuming a 25-year operational lifespan, it can continue to be supplied with desalinated water until 2028 (earliest) and 2033 (latest), while the industrial areas would continue being supplied from SWDP until 2033-2035, as they were built more recently (in 2005 and 2007 respectively). Yet, drinking water could be secured a couple of years more, whereas the population will continue growing at an average rate of 1,22% per year.

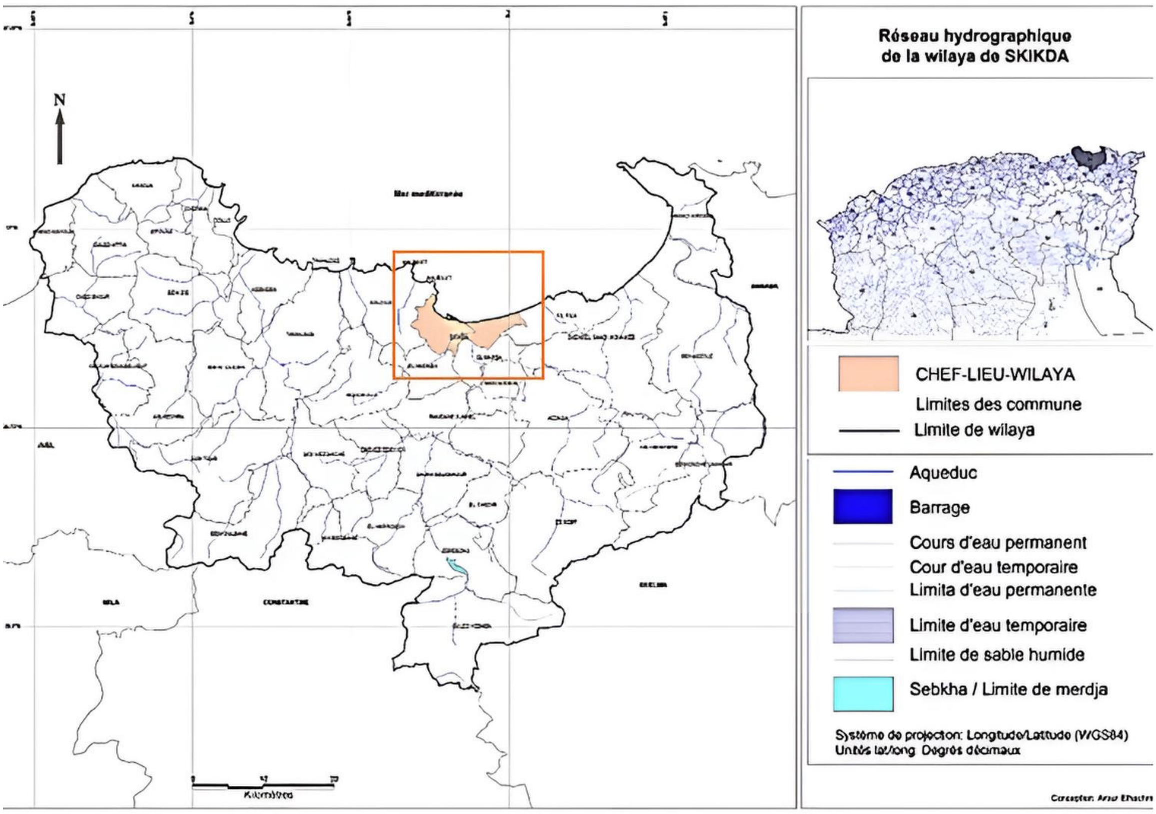



**Figure.7** *SWDP in coastal municipalities- Wilaya of Skikda (completed by the author using the base map of www.decoupageadministratifalgerie.com)*

**Analysis of the Skikda case study**: Referring to the Master Plan for Tourism development in Algeria, Skikda remains attractive. It is intensifying and extending the port zone while developing petrochemical, biotechnology, mechanics and metallurgy (SNAT, 2030). Within that new growing hub, seaside tourism is being developed through high standing tourist villages notably (SDAT, 2025). Furthermore, several housing programs are planned or under construction in order to answer an increasing demand. The urbanized area represented around 78,5% of the wilaya total surface resulting in 280 inhab/km2 (according to the wilaya website). Yet, the wilaya is classified as a medium to low-density urban area (Based on typical classifications derived from urban studies and density analyses, notably those inspired by UN-Habitat frameworks). It is calling for investment in various economic sectors, including tourism, agriculture, and the transformation industry (materials, agri-food, steelmaking, textiles, etc.).

# DISCUSSION

## *Geography of SWDPs, Water Availability, and Demand*

The spatial distribution of SWDPs in Algeria follows a territorial logic that aligns with regional water deficits. These facilities are concentrated along the coastline, particularly in the western regions, where freshwater resources are acutely limited. For instance, based on available data, the wilaya of Tlemcen records an annual water availability of only 152 m³ per capita. Similarly, the wilaya of Oran is experiencing a sharp reduction in water availability—298 m³ per capita per year—due to declining precipitation, overexploitation of aquifers, and pollution. These figures fall well below the international water stress threshold of 1,000 m³ per capita per year. Even in Algiers, often prioritized in water supply efforts, the figure reaches only 78.85 m³ per capita per year. The wilaya of Skikda stands as an exception, with an availability of 1,293 m³ per capita per year.

These conditions highlight the growing reliance on non-conventional water resources despite their significant environmental impacts at local and regional scales (Le Quesne and al, 2024). In this context, seawater desalination emerges as a response to both structural deficits (e.g., regional inequalities, recurrent droughts) and circumstantial pressures (e.g., interannual variability, prolonged dry spells). Concurrently, water demand is increasing significantly due to demographic growth, the concentration of economic activities along the coast, the expansion of the tourism sector (as encouraged by the national tourism development plan), and industrial ambitions (such as the industrial zones in Arzew and Skikda)[20].

In response, the Government has invested heavily in the development of desalination infrastructure, with numerous SWDPs currently operational or under construction. A parallel effort is underway to integrate renewable energy sources (e.g. solar energy) to enhance the long-term energy sustainability of these systems.

However, several dimensions of «water security» raise questions about the long-term viability of this option:

- Availability: Locally increased by SWDPs, but conventional water sources continue to decline overall.
- Accessibility and affordability: Currently ensured through subsidies, but long-term sustainability is threatened by rising energy, treatment, and maintenance costs.
- Reliability: SWDPs have a limited lifespan (typically 25–30 years) and are sensitive to seawater quality (e.g., pollution, suspended solids).
- Quality and continuity: Although water quality is controlled, distribution remains intermittent in some areas, including Algiers and Oran.
- Vulnerability: SWDPs are exposed to natural hazards (e.g., erosion, marine submersion, sea-level rise) and anthropogenic pressures (e.g., coastal morphology changes due to urban expansion and pollution).

## *SWDPs and Integrated Coastal Zone Management (ICZM)*

The concentration of SWDPs along the coastline raises critical concerns for spatial planning and governance. The coastal zone already hosts over half of the national population, most economic infrastructure, and numerous industrial activities—all of which are frequently in conflict with ecosystem conservation imperatives.

The current trajectories of coastal development in Tlemcen, Oran, Algiers, and Skikda, while aligned with Algeria's national strategic planning frameworks (SDAT 2025 and SNAT 2030), reveal planning gaps when examined through the lens of Integrated Coastal Zone Management (ICZM).

20 By providing specific data related to water availability, including both conventional and non-conventional resources, current and projected water stress could have been assessed. However, water consumption and per capita allocation are generally not reported at the municipality scale. Regarding water supply, the wilaya is divided into zones, which are further subdivided into centers. Additionally, water infrastructures, which are managed by a public firm, may supply more than one municipality.

These initiatives indicate that coastal planning remains fragmented, while cross-sectoral coordination is still limited as evidenced by the juxtaposition of high-end tourism infrastructure with industrial and residential expansion, often within ecologically sensitive coastal zones. In Skikda and Oran, for instance, the concurrent development of petrochemical hubs and seaside tourism zones exemplifies a lack of integration between environmental, industrial, and tourism planning—contradicting the holistic ethos of ICZM. To date, only three coastal development plans have been formally adopted (Algiers, Oran, and Béjaïa), and the ICZM 2030 report highlights a persistent lack of intersectoral coordination.

The continued expansion of coastal metropolitan areas (e.g., Algiers, Oran, Annaba) may exacerbate existing pressures, contravening the principles of adaptation, ecosystem-based management, and precaution that ICZM promotes. Urbanization dynamics—both planned and informal—continue to threaten ecologically sensitive areas. The close proximity of industrial zones, planned and informal settlements, and desalination infrastructure amplifies local vulnerabilities. As an example, urbanized area along the coastal zone is increasing in the wilaya of Tlemcen, Oran, Algiers and Skikda, by about 14,4%, 28,7%, 36,7% and 31,6% respectively (Mezouar, 2022).

Regarding long-term spatial planning, although each wilaya is equipped with master plans and zoning instruments, their implementation rather appears reactive, while informal urbanization continues to grow, the continued urbanization of the Mitidja plain in Algiers and the ongoing degradation of Oran's coastline are relevant examples of that process. Despite the existence of regulatory frameworks such as the Coastal Land-Use Plan and Law 02-2002, suggest that spatial planning appears neither sufficiently nor effectively integrated into long-term urban and socio-economic development strategies. However, the availability of local urban planning documents would provide relevant insights, enabling a more accurate assessment of their alignment with precautionary principles as part of environmental protection approaches.

With respect to protection of coastal biodiversity and ecosystems, although some marine and coastal areas—particularly around Oran and Algiers— are designated as marine protected areas, urban and industrial encroachment persists. This indicates a gap between legal provisions and actual practices in environmental governance and monitoring mechanisms.
The safeguarding of natural resources and livelihoods, particularly agricultural land and water resources, appears insufficiently prioritized. The conversion of fertile agricultural zones, notably in Algiers and Tlemcen, to accommodate housing and tourism projects may undermine long-term food security and rural livelihoods. Furthermore, that raises critical questions about the sustainability of such growth patterns in the context of water stress.

Coastal planning remains fragmented. To date, only three coastal development plans have been formally adopted (Algiers, Oran, and Béjaïa), and the ICZM 2030 report highlights a persistent lack of intersectoral coordination. The continued expansion of coastal metropolitan areas (e.g., Algiers, Oran, Annaba) may exacerbate existing pressures, contravening the principles of adaptation, ecosystem-based management, and precaution that ICZM promotes. Urbanization dynamics—both planned and informal—continue to threaten ecologically sensitive areas. The close proximity of industrial zones, planned and informal settlements, and desalination infrastructure amplifies local vulnerabilities. As an example, urbanized area along the coastal zone is increasing in the wilaya of Tlemcen, Oran, Algiers and Skikda, by about 14,4%, 28,7%, 36,7% and 31,6% respectively (Mezouar, 2022).

## *Prospects and Policy Levers*

The municipalities of Tlemcen, Oran, Algiers, and Skikda exemplify distinct coastal dynamics shaped by specific geographic, climatic, and socio-economic contexts. Each reflects a different configuration of urban development, demographic trends, and economic specialization—from agriculture and tourism to heavy industry and port logistics. Despite these contrasts, all four municipalities share a structural reliance on seawater desalination to secure drinking water supply amidst increasing demand. However, the lifespan and coverage of existing desalination infrastructure vary significantly, exposing varying degrees of vulnerability. With ongoing urban expansion, touristic ambitions, and industrial pressures, ensuring long-term water security in these coastal regions requires more than technical solutions: it demands anticipatory governance, integrated planning, and context-sensitive strategies tailored to each territory's profile.

Tlemcen stands out for its agricultural profile and dispersed coastal urbanization, where desalination supports a limited number of municipalities. Its relatively moderate growth allows current capacities to suffice for now, though they are nearing obsolescence. Oran, in contrast, combines high urban pressure, major industrial demand, and dependency on long-distance transfers, making its water security more fragile despite an extensive desalination system. Algiers, with its dense urban fabric and central political role, confronts critical land-use tensions. Though it hosts several SWDPs, these only partially cover local needs, while major projects threaten ecological balance and fertile peri-urban land. Skikda benefits from abundant rainfall and moderate demographic pressure, yet relies on a single desalinated water supply point concentrated in the capital municipality. Its intensifying industrialization and port activities may offset its climatic advantage. Together, these cases reveal the need for diversified, resilient water supply strategies and better alignment between water infrastructure planning, territorial development, and coastal ecosystem protection.

The key issue is not to reject desalination outright—it remains a strategic solution in a context of resource scarcity—but rather to reposition it within a broader, more integrated vision. Key policy levers can be prioritized as follows:

1. Integrating SWDPs more systematically into territorial planning instruments (urban planning, ICZM, energy strategies): The review of local planning documents can reveal the articulation level between water infrastructure development and territorial instruments like PDAU (urban master plans) or ICZM frameworks. This observation appears to be common to the four case studies, but it needs to be confirmed and assessed. In any case, cross-sectoral planning coherence needs to be reinforced.
2. Reinforcing local governance and institutional capacities to anticipate climate change impacts and manage emerging risks: Across all cases, local actors have limited involvement in water infrastructure planning, with decisions largely centralized. Climate risks—such as saltwater intrusion or seasonal shortages—cannot be anticipated at the municipal level. The need to build institutional capacities and foster multi-level coordination is therefore a crucial condition for adaptive and sustainable water management.
3. Strengthening environmental monitoring of coastal impacts (e.g., brine discharge, cumulative effects): According to the legal texts, environmental impact assessments are mandatory, especially regarding brine discharge effects. This is especially important in the case of Skikda and Oran, where SDWPs supply industrial and port areas in addition to providing the population with drinking water.
4. Promoting water-use efficiency: The analysis of Oran and Skikda, both experiencing increasing pressure from tourism and industry, shows that water consumption remains high, particularly in agriculture (e.g., irrigated citrus in Skikda) and expanding tourism facilities. This underscores the need to shift from a purely supply-oriented logic to a demand-management approach, aligned with local availability thresholds, and aimed at improving efficiency and optimizing the use of both conventional and non-conventional water resources.
5. Enhancing wastewater recovery and reuse: The analysis demonstrates significant potential in Algiers in particular as the wilaya has appropriate infrastructure. For instance, many wastewater reuse irrigating pilot projects and recycling processes are already experienced in Algeria (e.g., the Wilayas of Ouargla, Constantine, Laghouat, Biskra) (Aroua, 2022).

While most of these actions are largely integrated into the National Water Plan, their implementation and long-term continuity require continued policy commitment. Furthermore, the integration of SWDPs into territorial planning documents is an essential step toward improved coherence and sustainability. Countries across the Mediterranean and beyond are grappling with similar dilemmas. Algeria has laid the groundwork for a short- and medium-term response. The next step is to consolidate these gains, acknowledge existing limitations, and initiate a transition toward an integrated, resilient, and equitable water resource management framework.

## CONCLUSION

This paper set out to critically assess the current and projected role of seawater desalination plants (SWDPs) in securing Algeria's water supply, through the combined lens of spatial planning and integrated coastal zone governance. Drawing on a mixed-methods approach—both qualitative and quantitative—the study sheds light on the complex interplay between necessity and uncertainty that characterizes the recourse to desalination in a context of growing hydric stress.

Several methodological and empirical limitations must nonetheless be acknowledged. In the absence of reliable commune-level data, demographic projections to 2030 were extrapolated from wilaya-level growth rates. Likewise, estimates of water potential were based on watershed or wilaya-level figures. While the 2030 time horizon is consistent with major national strategies—such as the SNAT and the National Tourism Strategy—it no longer qualifies as long-term planning. With regard to water resources, a 50- to 100- year strategic planning horizon is indeed now widely recommended (Aroua, 2018).

Additionally, this study was unable to integrate spatial development data from local planning tools such as the Wilaya Development Plan and the Urban Master Plan, which would have yielded valuable insights into future urban expansions, housing developments, and the spatial footprint of water infrastructure. These documents were not available for consultation at the time of writing. Finally, the assessment of SWDPs focused exclusively on potable water production, excluding industrial demand due to a lack of sector-specific data—a critical blind spot, given the industrial ambitions of coastal development poles such as Arzew and Skikda.

Despite these limitations, the central value of this work lies not in data exhaustiveness, but in the articulation of a fundamental issue: the structural and systemic uncertainty that surrounds both conventional and non-conventional water resources, albeit for different reasons. Far from dispelling doubt, the analysis challenges the perception of desalination as a panacea and invites a critical re-evaluation of its long-term viability as a development strategy.
Any national development strategy cannot be credibly based on unresolved uncertainties. Yet it is precisely uncertainty that forms the foundation of the IPCC's climate scenarios, which nevertheless guide global policymaking. This paradox prompts a broader reflection: do we truly have a choice? Tentatively, the answer is yes—but it is a choice that demands vision and political courage.

It requires resisting the technocentric momentum and reorienting policy toward the hydrological and ecological carrying capacities of territories, as practiced by earlier societies: through frugality, prudence, and a deep-seated respect for the natural world—one that humanity neither can, nor has any interest in, overpowering. Thus, there is little merit in perpetuating a logic of domination over nature; rather, the path forward lies in re-establishing balance and cohabitation.

Ultimately, the analysis conducted underscores the necessity of a nuanced and constructive evaluation of the current and future role of seawater desalination plants (SWDPs) in securing Algeria's water supply. While their deployment reflects a strategic attempt to anticipate and respond to a growing water deficit, it is now imperative to reconsider this orientation in light of the principles of sustainable territorial development and integrated coastal zone management (ICZM). In other words, the objective is not to challenge a strategy that may well be necessary at present, but rather to assess its limitations and explore potential development evolutions by identifying alternative or complementary levers for action.

In sum, while Algeria has initiated a response to immediate and medium-term water supply challenges, the deeper task ahead lies in recognizing the limits of current trajectories and undertaking a transition toward integrated, adaptive, and ecologically grounded water governance—one that is not only resilient and reactive, but also proactive and equitable and rooted in the local realities.

The deployment of seawater desalination plants in Algeria raises several critical issues[21], particularly regarding strategic alignment with water security as defined by UN-Water, territorial planning policies, and the principles of integrated coastal zone management. While these infrastructures address the imperative of securing potable water supply in a country facing chronic hydrological deficits, their siting must be rigorously balanced and coordinated with the specific water availability within coastal areas, especially in contexts of rapid urban and industrial expansion. Desalination plants must be strategically positioned to maximize operational efficiency, aligning with local water demand while considering the limited availability of conventional resources.

As an example, Algeria is rated as water insecure, with national water security scoring 58 out of 100. For comparison, the United Arab Emirates are rated moderately secure, with national water security scoring 66 out of 100, and Spain is rated secure, with national water security scoring 77 out of 100. Gulf countries are profoundly reliant on seawater desalination, with Masdar city setting an ambitious target to reduce its consumption by 80%, aiming to alleviate both energy demand and the environmental impact of brine discharge. However, seawater desalination plants exert a range of impacts on the marine environment at a regional scale, which are compounded by multiple human activities in the Gulf. While desalination in the Gulf region is essential for socio-economic development and is expected to expand further to ensure drinking water supply, it simultaneously undermines the objectives of sustainable development.

Similarly, in Spain's southeastern coast, desalination has played a pivotal role in sustaining intensive agriculture and supporting urban-tourist expansion. Yet it has encouraged further urbanization and agricultural intensification in ecologically sensitive coastal zones (Bernabé-Crespo and al, 2019). Similarly, in the United Arab Emirates, it has enabled the growth of megacities like Dubai, increasing energy demand and placing additional stress on marine environments due to brine disposal and habitat disruption. These two examples illustrate how the promise of technological resilience can paradoxically drive land-use changes that undermine environmental sustainability, especially in the absence of wise water governance and integrated spatial planning frameworks.

21 B Beyond territorial coherence and alignment with water needs and spatial planning policies, the deployment of desalination plants raises several major challenges of a technical, economic, environmental, and social nature, such as energy sustainability, economic cost, and environmental impact.

# IMPROVING GOVERNANCE AND REGULATORY TOOLS FOR MORE SUSTAINABLE WATER MANAGEMENT IN ALGERIA

AUTHORS : BOUZNAD IMAD EDDINE, ZEBSA RABAH, ZIOUCH OMAR RAMZI, BENGUSMIA DJAMEL

Oued Kramis Dam in the Wilaya of Mostaganem © ali mehadji

## Abstract

Seawater desalination is a crucial solution to Algeria's water crisis. However, this sector faces significant sustainability challenges, particularly regarding water resource management. This study examines the impact of water management on desalination, with a specific focus on integrating the reuse of treated non-conventional water. The research was conducted in selected pilot provinces in Algeria, providing region-specific insights into sustainable desalination practices. The main objective is to optimize water resource utilization while minimizing environmental and economic impacts. To achieve this, the Water Evaluation and Planning System (WEAP) model was used to simulate water demand and assess future water resource needs. This tool supports infrastructure planning, particularly for desalination and treated wastewater reuse systems. Additionally, the K-means clustering method and the Analytic Hierarchy Process (AHP) were applied to identify the area's most vulnerable to water stress, considering climatic, demographic, and hydrological factors. Our results indicate the presence of vulnerability zones that require particular attention. For instance, Oran exhibits extreme vulnerability to water scarcity, whereas El Tarf presents a more favorable situation with lower vulnerability. The analysis of the temporal patterns of water demand projected until 2050 reveals a generalized increase across all regions, although the intensity of this growth varies significantly between provinces. For example, water demand in Oran is expected to increase by 208.6%, reaching 260.1 Mm³ in 2050, while Algiers and Setif will experience increases of 41.2% (reaching 182.4 Mm³) and 172.3% (reaching 153.7 Mm³), respectively. These trends reflect growing pressure on water resources. The projected evolution of unmet water demand in major Algerian provinces suggests a substantial worsening of water deficits by 2050 in the absence of desalinated water. A cross-analysis of treated wastewater return flows and unmet water demand (UWD) in Algeria highlights strategic opportunities for more efficient water resource management by 2050, positioning wastewater reuse as a key lever for alleviating water supply pressures. This combined approach will help target regions most at risk of water shortages while promoting a more rational management of desalinated and reused water. The findings of this study will provide concrete recommendations to strengthen water resource governance, adopting a more integrated and sustainable approach aligned with international commitments, including those from COP23 and the Barcelona Convention.

**Keywords:** Desalination, Wastewater reuse, Water management, water stress WEAP, Clustering, Sustainability.

## INTRODUCTION

Faced with the increasing scarcity of freshwater resources, seawater desalination has become an essential technological solution for regions experiencing severe water stress (Rodoula K, 2025; Mitiche R, 2010). By harnessing the oceans, which account for nearly 97% of the world's water reserves (Wei Han Tu, 2024), this technology provides a virtually unlimited source of drinking water, contributing to sustainable development goals (Sajna M.S., 2024). However, despite its potential, desalination faces major challenges, including high energy costs, environmental impacts related to brine discharge (Gamboa G, 2025; Bianchelli S, 2022), and the need for optimal integration into existing water systems (Grau-Cano S, 2025; Kherbache N, 2020), particularly in terms of adapting current distribution networks—which may be outdated or insufficient—to handle the variable supply and localized production of desalinated water. This issue is particularly critical as shifting climate patterns, prolonged droughts, and excessive extraction of freshwater sources continue to intensify pressure on global water availability (Heck et al., 2017; Heck et al., 2018). Conventional drinking water sources are becoming increasingly unreliable, making desalination a crucial strategy for addressing water scarcity in coastal areas and improving overall water security (Sola et al., 2024). However, the widespread adoption of desalination technologies is accompanied by significant challenges. Chief among these are the substantial financial costs associated with constructing and maintaining desalination infrastructure, as well as the high electricity demands of processes such as reverse osmosis (RO) and thermal distillation (Azevedo et al., 2023). According to Plan Bleu (2023), the cost of producing 1 m³ of desalinated seawater in the Mediterranean region typically ranges from €0.5 to €1.5, depending on the technology and local conditions, with energy costs representing up to 50% of the total operating expenses. The considerable initial investment and continuous operational expenses often hinder the feasibility of desalination projects, particularly in economically constrained regions. Additionally, the energy-intensive nature of desalination raises environmental concerns, notably its contribution to greenhouse gas emissions and the ecological consequences of increased energy consumption (Nassrullah et al., 2020; Xu et al., 2013). Another major environmental issue is the disposal of concentrated brine, which, when released into marine environments, can disrupt ecosystems and pose a threat to aquatic life (Lee et al., 2019; Alazmi et al., 2023).

Sustainability remains a key challenge in desalination efforts. Emerging technologies, such as membrane distillation and solar-powered desalination systems, seek to reduce environmental impacts (Kaur et al., 2024). Improvements in energy efficiency and the integration of hybrid desalination methods have the potential to minimize the ecological footprint of these processes, fostering a more sustainable approach to water production (Berenguel-Felices et al., 2020). However, as many of these innovations are still in early stages of development, the desalination sector continues to face the complex task of balancing water security benefits with economic and environmental trade-offs.

In Algeria, a country particularly vulnerable to water shortages due to its arid climate and recurring droughts ( Meddi M, 2024; Khacheba R, 2018; Derradji et al., 2023), desalination plays a strategic role in water policy (Yasmine K, 2025; Abdelkrim Sadi, 2004). With infrastructures such as the Hamma desalination plant, capable of producing 500,000 m³/day (Amokrane M, 2021), the country is relying on this technology to secure its water supply.

Spatial disparities in water resource access are particularly pronounced in Algeria. The eastern region benefits from more developed hydraulic infrastructure, supported by large dams ensuring better water flow regulation. In contrast, the western region and the High Plateaus, which rely on smaller reservoirs, remain highly vulnerable to climate fluctuations and periods of water stress. Moreover, coastal areas, experiencing sustained demographic growth, face an increasing imbalance between water supply and demand, despite the presence of dedicated supply infrastructures.

From a climatic perspective, the region has a Mediterranean climate with annual precipitation ranging from 400 to 900 mm, with significant variability depending on the locality (ANRH, 2023). However, the spatial and temporal distribution of rainfall remains uneven, exacerbating water stress periods, especially in summer. In response to these challenges, the Algerian government has implemented a resource diversification policy, emphasizing desalination as a strategic alternative.

This article provides an in-depth analysis of the role of desalination in water resource management, highlighting its benefits, limitations, and the necessary innovations for making it a sustainable solution. Special attention will be given to the Algerian context, where public policies, subsidized costs (Abdelhafid Benahmed, 2025), and alternative energy sources play a crucial role in the future viability of this technology. Finally, the study will explore potential improvements, including the reuse of treated wastewater and better-integrated water resource management in response to climate challenges (Palatnik R, 2025; Drouiche N, 2012).

This research evaluates the impact of desalination and wastewater reuse on water resource management in Algeria by combining the WEAP model with K-means clustering. This approach helps identify areas vulnerable to water stress and optimize water resource utilization. The analysis will lead to practical recommendations for effective governance and sustainable infrastructure planning. It also aims to provide policymakers and industry stakeholders with strategic guidance for integrated water resource management, balancing water security, economic efficiency, and environmental sustainability while considering local specificities and international best practices.

## METHODOLOGY

### *Study Area Presentation*

The study area includes 9 coastal provinces of Algeria that benefit from seawater desalination, as well as those scheduled to be served by this technology under national strategies for securing water supply. This approach aligns with Algeria's national water strategy, which aims to increase seawater desalination capacity to over 3.8 million m³/day by 2030 to meet the growing urban demand and reduce dependency on surface and groundwater resources (Ministry of Water Resources and Security, Algeria, 2022). Administratively, it encompasses several provinces along the coastline, notably Algiers, Oran, Mostaganem, Chlef, Tipaza, Boumerdès, Béjaïa, Skikda, and Annaba, which are directly supplied by operational desalination plants. 2 additional inland provinces, such as Blida and Sétif, are also included in the study due to water transfer projects aimed at providing them with an additional resource to address water shortages.

This study area is characterized by a high population density and rapid urbanization rates, leading to increasing pressure on water resources. With an estimated population of over 25 million inhabitants, representing nearly 60% of the national population (ONS, 2023), these provinces experience high demand for drinking water, particularly in major urban centers like Algiers, Oran, and Annaba. Conventional water resources, sourced from dams and aquifers, are increasingly insufficient to meet these needs due to irregular rainfall, reservoir sedimentation, and overexploitation of aquifers.

Algeria mainly relies on its hydraulic infrastructure to meet the growing demand for drinking and agricultural water. The country has more than 80 dams with a total storage capacity of 8.4 billion cubic meters (ANBT, 2023). Algeria's erosion rate is considered the highest in the Maghreb, exceeding 2,000 tons/km² per year for most watersheds in the Tell region. While reservoir sedimentation remains the most quantified consequence of soil erosion (BENFETTA H, et al., 2016), other sectors are also affected by sediment transport. For example, the Beni Haroun Dam (960 million cubic meters) has seen its net capacity decrease to 864 million cubic meters, while infrastructures like Aïn Zada and Draa Diss have experienced significant reductions, impacting water supply to key regions (ANBT, 2022).

The study area currently hosts several operational desalination plants, the most significant being Magtaa (Oran, 500,000 m³/day), Fouka (Tipaza, 120,000 m³/day), Cap Djinet (Boumerdès, 100,000 m³/day), and El Mactaa (Mostaganem, 200,000 m³/day). Additional plants are being planned or expanded to ensure water supply to inland provinces.

The inclusion of non-coastal provinces in this study is justified by the growing interconnectivity of Algeria's water supply infrastructure, particularly the strategic expansion of transfer networks originating from coastal desalination plants. While desalination facilities are predominantly located along the Mediterranean coast, their impact increasingly extends inland through extensive pipeline systems. Notable examples include the transfer of desalinated water from the Algiers plant to the neighboring province of Blida, and from the Mostaganem plant to inland areas such as Relizane. These initiatives are part of a broader national strategy to mitigate regional water disparities by redistributing water from surplus to deficit zones.

This integrated water management approach reflects a shift from isolated, locally-focused solutions to a more coordinated national water grid. It not only addresses the acute water shortages faced by inland provinces—often exacerbated by drought, declining aquifer levels, and climate variability—but also reduces dependence on overstressed groundwater sources in the High Plateaus. By linking desalination with hydraulic interconnections, Algeria is leveraging its coastal advantage to support inland resilience, thereby promoting equitable access to water across regions. This strategy aligns with long-term sustainability goals and enhances the flexibility and reliability of the country's water supply system.

Furthermore, groundwater resources were not included in this model due to the lack of precise quantitative data and detailed aquifer explorations. Additionally, Algerian authorities prioritize the preservation of these aquifers for agriculture and as a strategic reserve, particularly since several aquifers have experienced alarming declines in water levels over recent decades due to successive droughts.

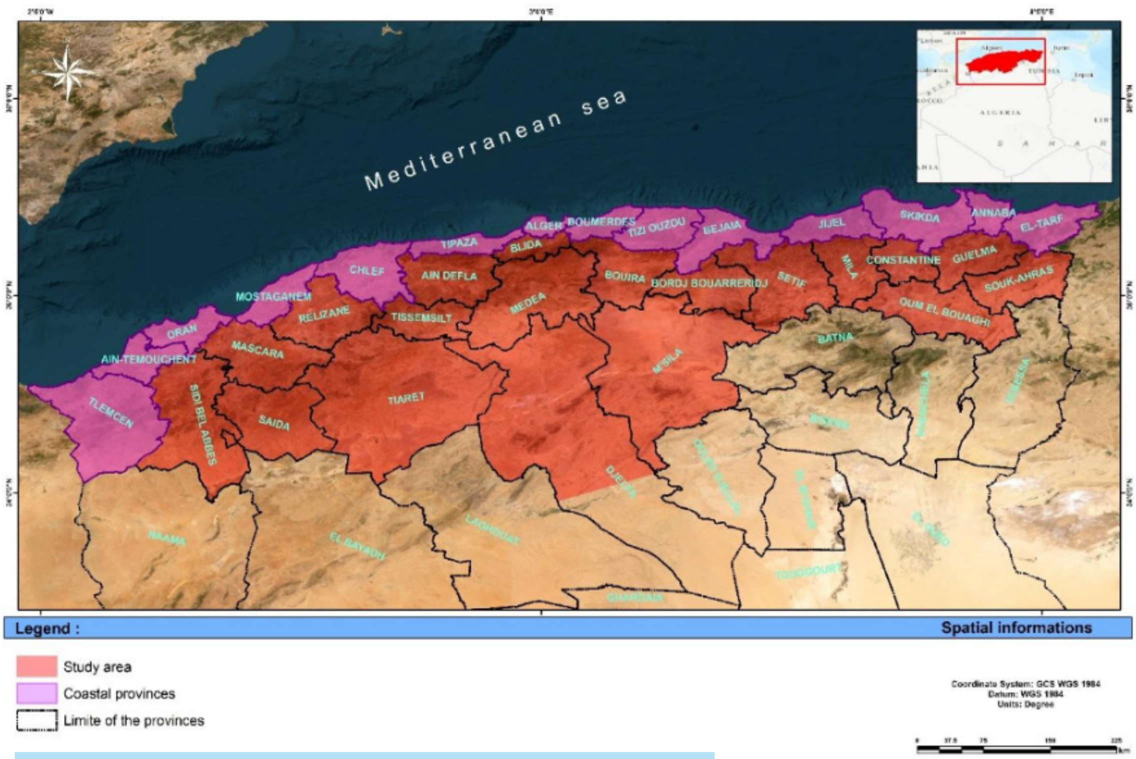



**Figure.1** *Geographical Location of the Study Area in Algeria*

This research aims to enhance governance and regulations in Algeria for the sustainable management of water, integrating desalination and the reuse of non-conventional water, while adhering to the sustainability criteria set forth by COP23 and the Barcelona Convention. The methodology consists of several main components:

## *Clustering and AHP method*

As part of this study, we applied the K-Means clustering algorithm to time series data covering three essential variables:

- Population: Total number of inhabitants in each province, expressed in number of persons, based on data from the Office National des Statistiques (ONS, 2023).
- Precipitation: Annual total rainfall measured in millimeters per year (mm/year), derived from CHIRPS remote sensing datasets.
- Aridity index: A dimensionless indicator calculated as the ratio between mean annual precipitation and potential evapotranspiration (PET), based on FAO-UNEP classification, used to characterize climatic dryness.

The main objective was to identify and classify areas vulnerable to water stress while considering demographic and climatic dynamics. The approach adopted is based on an optimized segmentation of territories into homogeneous groups, enabling analysis of interactions between population density and available water resources. Through this classification, it becomes possible to detect regions where anthropogenic pressure on water resources is strongest, thus facilitating the development of sustainable management strategies and adaptation to changing climatic conditions.

The study assesses vulnerability to water shortages through an integrated approach considering climatic, hydrological, infrastructural and socio-economic factors. The objective is to identify at-risk areas to optimize water resource management.

Six major criteria are analyzed: (1) Aquifers, essential for drinking water supply and irrigation, where overexploitation can lead to resource depletion – measured through groundwater levels (in meters), variations in stored volumes (in million cubic meters), and abstraction rates (in cubic meters per year);(2) Drought vulnerability, where low rainfall and prolonged dry periods worsen water stress – assessed using metrics such as annual rainfall (in mm/year), the Standardized  Index de sécheresse. (3) Hydraulic infrastructure, such as dams and desalination plants, whose inadequacy or inefficiency increases shortage risks – evaluated through storage capacity (in million cubic meters), desalination output (in cubic meters per day). (4) Water pressure, linked to growing demand for domestic, increasing pressure on available resources – quantified using total water demand (in cubic meters per year), and the water stress index (expressed as a percentage); (5) Surface water availability, with dams and wadis playing a crucial role in water supply and reservoir filling levels (percentage of total capacity). (6) Population density, a key factor exerting additional pressure on water infrastructure – captured through inhabitants per square kilometer, urbanization rates (percentage of population living in urban areas).

Water shortage vulnerability assessment relies on a multicriteria approach integrating data collection and analysis, Analytic Hierarchy Process (AHP) for factor weighting, and result aggregation to establish a global vulnerability index. First, hydrological, socio-economic and infrastructural data are collected, then reclassified into numerical values on a standardized vulnerability scale. Each variable (e.g., precipitation, aridity index, population density, groundwater availability) is translated into a vulnerability score typically ranging from 1 (low vulnerability) to 5 (very high vulnerability), based on predefined quantitative thresholds. For instance, areas with very low precipitation or a highly arid climate will receive higher vulnerability scores, while regions with abundant renewable water resources and strong infrastructure will be scored lower. Similarly, densely populated zones or those experiencing a rapid decline in groundwater levels are considered more vulnerable. This scoring system allows us to interpret what "low" to "very high" vulnerability means concretely for each variable, facilitating a transparent and replicable evaluation of water stress exposure across different regions.

Each criterion is weighted according to its relative importance, with groundwater representing the predominant factor (32%), followed by infrastructure (18%), surface water and population (15% each), drought (12%) and finally water pressure (8%). Weighting consistency is verified through calculation of the consistency index and ratio, allowing for value adjustments to improve result reliability by reducing the consistency ratio from 25% to 8%. Finally, integration of weighted data enables generation of a global vulnerability index, resulting in a ranking of provinces according to their exposure level to water stress. This methodology thus provides an essential decision-support tool for optimized and sustainable water resource management.

### *WEAP Model (Water Evaluation and Planning)*

The WEAP model will be employed to simulate water demand at both regional and national scales, integrating demographic projections, climate change scenarios, and socio-economic factors. This modeling approach will evaluate the necessity for desalination and wastewater reuse while identifying priority areas for investment in water infrastructure.

This study utilizes the WEAP software (Water Evaluation and Planning), developed by the Stockholm Environment Institute (SEI, 2008), as a key tool for integrated water resource management. WEAP functions as a comprehensive modeling platform that incorporates various elements such as climate, hydrology, land use, infrastructure, and water management priorities within a watershed-based framework (YATES D. et al., 2005). Its operation is founded on the principle of water balance accounting, allowing users to represent key components of the water system, including supply sources (rivers, aquifers, and reservoirs), withdrawals, consumption demands, and ecosystem needs (HERVE L. et al., 2003). Given the growing need for adaptive water management strategies, WEAP has been extensively applied worldwide to analyze complex water systems and support decision-making in water resource planning (IRENE M. JOHANNSEN, 2016).

The WEAP model in this study is based on a conceptual representation of the supply network, where each system component (dam, desalination plant, urban center) is modeled as interconnected nodes linked by transmission lines (Figure 2). The analysis is conducted using a monthly water balance that integrates the system's main variables:

- Water resource availability, including surface and desalinated water
- Population water needs, derived from demographic projections and adopted allocation standards
- Resource allocation optimization, simulated using a linear optimization model to identify potential deficits and evaluate the efficiency of existing infrastructure
- The integration of desalination plants in the model follows a phased approach based on their actual commissioning dates:
- Plants operational before 2008 are included from the simulation start
- Plants commissioned between 2008 and 2014 are gradually introduced to observe their contribution to regional supply improvement
- Plants commissioned after 2014 are simulated according to their operational dates to analyze their progressive impact on the water balance of affected provinces

This methodology enables assessment of demand satisfaction over time and quantification of each plant's contribution to the water system's resilience.

## *Water Management Scenario Analysis*

Two distinct scenarios were defined to evaluate the impact of desalination plants on regional water balance:

**A.Reference Scenario (2008-2050)**

- Incorporates all hydraulic infrastructure, including desalination plants introduced progressively according to their actual commissioning
- Allows analysis of system evolution considering the cumulative effect of infrastructure development on water demand satisfaction

**B.Scenario Without Desalination Plants (2008-2050)**

- Simulates water management excluding the contribution of desalination plants
- Enables evaluation of drinking water deficit levels in the absence of these facilities and quantifies the dependence of affected provinces on desalination.

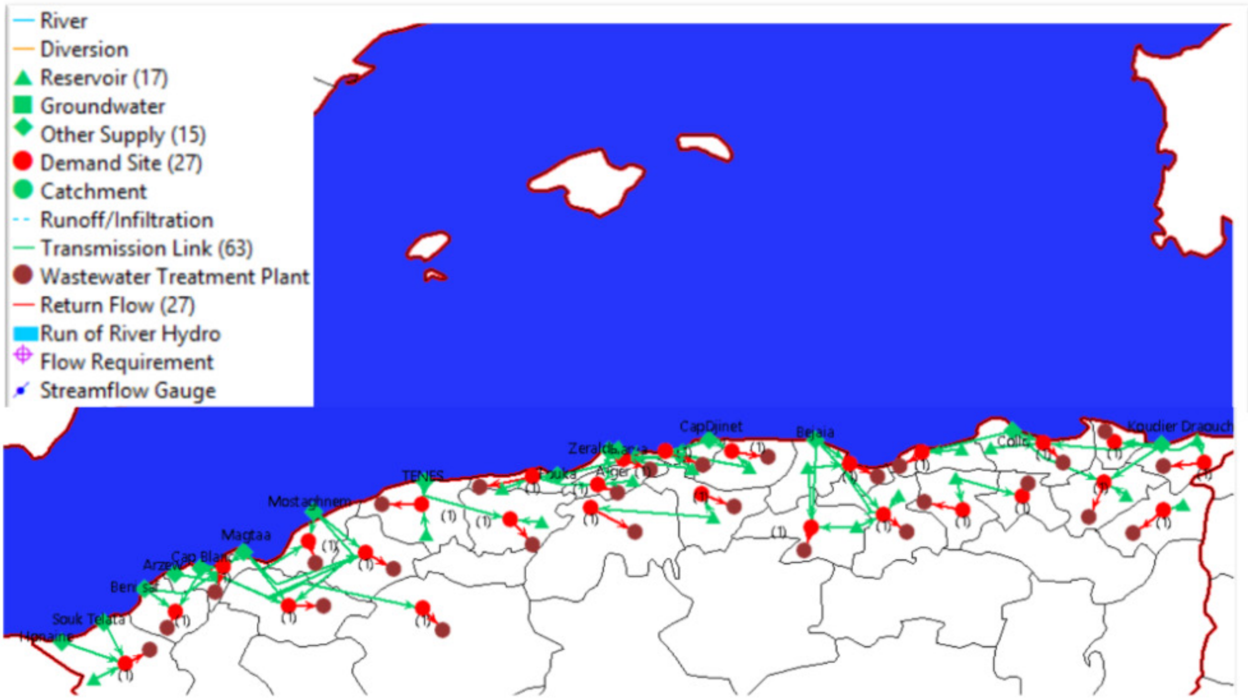



**Figure.2** *WEAP Model Schematic for Water Resource Management in Algeria*

The approach adopted under WEAP makes it possible to assess the evolution of water needs and the effectiveness of the infrastructures put in place. The comparative analysis of the two scenarios provides concrete elements on the role of desalination in meeting demand and on potential deficits in the absence of these plants. This approach thus provides a decision-making framework for optimizing long-term water resource management strategies.

### *Statistical Analysis*

We used R 4.3.3 to perform our statistical analyses (R Development Core Team, 2024). To identify similarities in water demand trends across provinces, a hierarchical clustering analysis was conducted using the «cluster» package in r. The Euclidean distance metric was used to compute the pairwise dissimilarity between provinces based on their water demand trends over time. We applied a hierarchical clustering approach (HCA) using the Ward.D2 linkage method. This method minimizes the variance within clusters.

### *Data Collection and Structuring*

The first stage of the study is based on the development of a detailed cartographic database, integrating several essential components. The demand sites correspond to the studied provinces, while the hydraulic infrastructures include desalination plants and dams ensuring their water supply. The demographic data comes from the 2008 census, taken as the reference year, and population growth is projected until 2050 based on specific growth rates for each province, interpolated from historical trends. For all simulations, a water allocation of 150 L/day/person was adopted. The data required for modeling were collected from official sources, including reports from the Ministry of Water Resources, the National Agency for Dams and Transfers (ANBT), as well as surveys and other available information databases.

## RESULTS AND DISCUSSION

### *Water Stress Vulnerability Mapping*

The application of the K-Means algorithm allowed for the segmentation of alternatives into homogeneous groups. The examination of cluster centroids highlights the existence of distinct groups characterized by differentiated performances. Some clusters group together alternatives showing high scores across several criteria, while others display weaker and more heterogeneous performances. This distribution suggests the presence of vulnerability zones requiring particular attention (Oran).

The AHP method enabled the ranking of alternatives according to their relative importance based on the defined criteria. The results show that the highest-ranked alternatives present high weighted scores, indicating strong alignment with priority criteria (Table 1).

A deeper analysis reveals that some alternatives, despite having good overall rankings, show significant disparities between criteria, suggesting variations in their multidimensional performance. This observation underscores the need to examine trade-offs between criteria in the final decision-making process. The cross-analysis of AHP and K-Means results with the water scarcity vulnerability map reveals several critical zones requiring priority attention. Figure 3 highlights provinces classified as having «very high» or «high» vulnerability, such as Oran and certain areas in Eastern Algeria (Souk-Ahras, Guelma). These regions also appear in the disadvantaged clusters identified by K-Means, confirming their vulnerability according to the analysis criteria.

Regions such as Oran show extreme vulnerability to water scarcity, which can be exacerbated by high water demand and limited resources. Areas like M'Sila and Djelfa, although having slightly lower vulnerability, also require careful management of water resources.

On the other hand, the province of El Tarf presents a more favorable situation. This can be attributed to better availability of water resources or more effective infrastructure management.

| Province | Pr | AI | POP | Groundwater | Drought | Infrastructure | Pressure | Surface Water | Total Vulne-rability | Vulne-rability Class |
|---|---|---|---|---|---|---|---|---|---|---|
| ORAN | 3 | 3 | 5 | 4 | 2 | 2 | 4 | 4 | **4.6** | Very High (5) |
| ALGIERS | 2 | 2 | 5 | 4 | 2 | 2 | 4 | 4 | **4.5** | High (4) |
| BORDJ BOU ARRERIDJ | 1 | 1 | 2 | 4 | 4 | 4 | 4 | 4 | **4.1** | High (4) |
| SETIF | 0 | 0 | 4 | 4 | 3 | 3 | 4 | 3 | **4.0** | High (4) |
| BLIDA | 2 | 2 | 3 | 3 | 2 | 2 | 4 | 4 | **3.9** | High (4) |
| ANNABA | 4 | 4 | 2 | 3 | 3 | 3 | 4 | 4 | **3.7** | High (4) |
| SKIKDA | 4 | 4 | 3 | 3 | 3 | 3 | 4 | 3 | **3.7** | High (4) |
| CHLEF | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 3 | **3.6** | High (4) |
| BOUMERDES | 2 | 2 | 2 | 3 | 3 | 3 | 4 | 3 | **3.4** | Moderate (3) |
| TIPAZA | 2 | 2 | 2 | 3 | 2 | 2 | 4 | 3 | **3.3** | Moderate (3) |
| CONSTANTINE | 0 | 0 | 3 | 3 | 3 | 3 | 4 | 3 | **3.3** | Moderate (3) |
| AIN-TE-MOUCHENT | 3 | 3 | 1 | 4 | 3 | 3 | 3 | 3 | **3.2** | Moderate (3) |
| MEDEA | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | **3.2** | Moderate (3) |
| SOUK-AHRAS | 0 | 0 | 2 | 3 | 4 | 4 | 3 | 3 | **3.2** | Moderate (3) |
| MASCARA | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | **3.1** | Moderate (3) |
| TIARET | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | **3.1** | Moderate (3) |
| RELIZANE | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | **3.1** | Moderate (3) |
| BOUIRA | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | **3.0** | Moderate (3) |
| MOSTAGANEM | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | **3.0** | Moderate (3) |
| TLEMCEN | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | **3.0** | Moderate (3) |
| GUELMA | 0 | 0 | 2 | 3 | 3 | 3 | 3 | 3 | **2.9** | Moderate (3) |
| TIZI OUZOU | 2 | 4 | 3 | 2 | 3 | 3 | 3 | 3 | **2.9** | Moderate (3) |
| SIDI BEL ABBES | 1 | 1 | 2 | 3 | 3 | 3 | 3 | 3 | **2.8** | Moderate (3) |
| MILA | 0 | 0 | 2 | 3 | 2 | 2 | 3 | 2 | **2.7** | Moderate (3) |
| BEJAIA | 2 | 0 | 2 | 2 | 3 | 3 | 3 | 3 | **2.5** | Low (2) |
| TISSEMSILT | 2 | 2 | 1 | 3 | 3 | 3 | 3 | 3 | **2.5** | Low (2) |
| SAIDA | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | **2.4** | Low (2) |
| JIJEL | 4 | 4 | 2 | 2 | 2 | 2 | 3 | 2 | **2.3** | Low (2) |
| EL-TARF | 4 | 4 | 1 | 2 | 2 | 2 | 3 | 4 | **2.0** | Very Low (1) |

**TABLE 2**
**Water Vulnerability Index by Province According to Stress Factors**

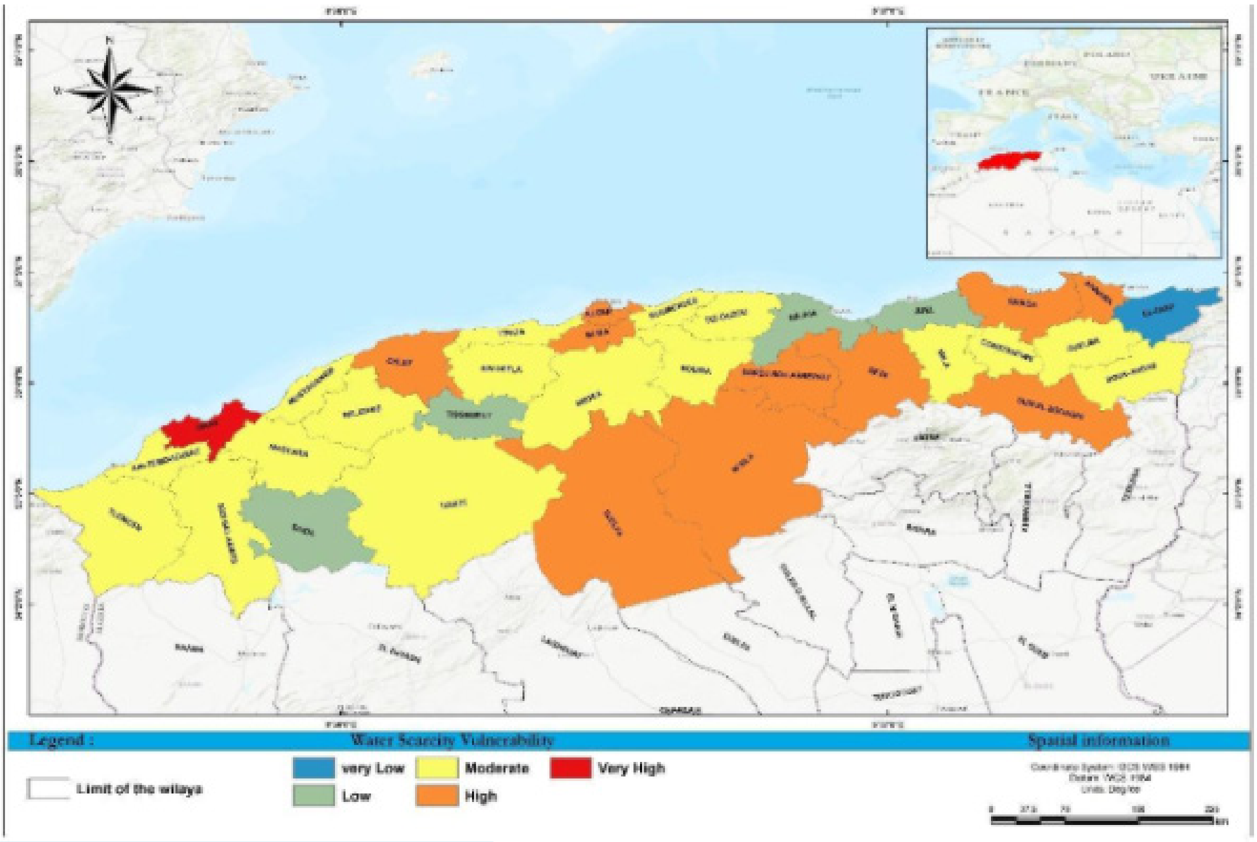



**Figure.3** *Water vulnerability map of northern Algeria's provinces*

The identification of vulnerable zones constitutes a major contribution of this study, as it enables directing efforts toward targeted improvement strategies. The results suggest that specific corrective actions, such as optimizing the most influential criteria in at-risk clusters, can improve the resilience of the concerned alternatives.

## *Water Demand (2008-2050)*

Figure 4 shows the projected evolution of water demand in several Algerian provinces over the period 2008-2050, according to a reference scenario. The analysis of the curves reveals a generalized increase in water demand across all regions, although the intensity of this growth varies considerably between provinces.

The analysis of water demand in Algeria, projected until 2050, highlights a generalized increase in needs, particularly marked in large urban areas. The results show a significant increase in Oran (+208.6%, reaching 260.1 Mm³ in 2050), Algiers (+41.2%, reaching 182.4 Mm³) and Sétif (+172.3%, reaching 153.7 Mm³), reflecting growing pressure on water resources. This trend is confirmed by the water vulnerability mapping, carried out using the AHP method, which identifies Oran as the most exposed province (vulnerability index > 0.85), followed by Sétif and Chlef, where the combination of climatic factors (precipitation < 300 mm/year), demographic factors (annual population growth > 2.1%) and infrastructure factors (access rate to hydraulic infrastructure < 65%) exacerbates water stress.

Furthermore, water demand in the High Plateaus and southeastern provinces, although lower in absolute value, shows a worrying growth (+146.8% compared to 2020), highlighting increasing needs for water transfer infrastructure. In contrast, some provinces such as Jijel and Béjaïa, although experiencing an increase in demand (+79.5% and +68.4% respectively), benefit from lower water vulnerability due to better availability of natural resources and more efficient storage infrastructure.

These findings underscore the need for an overhaul of water management policies in Algeria, with targeted investments: development of desalination (target: 2 billion m³/year by 2035), intensification of wastewater recycling (estimated potential of 40% of unmet demand) and strengthening of inter-basin transfer infrastructure to mitigate regional imbalances. Without appropriate measures, projections indicate that some provinces could face critical deficits, exceeding 148.9 Mm³ in Sétif and 136.6 Mm³ in Constantine after 2040, thereby compromising the country's water security.

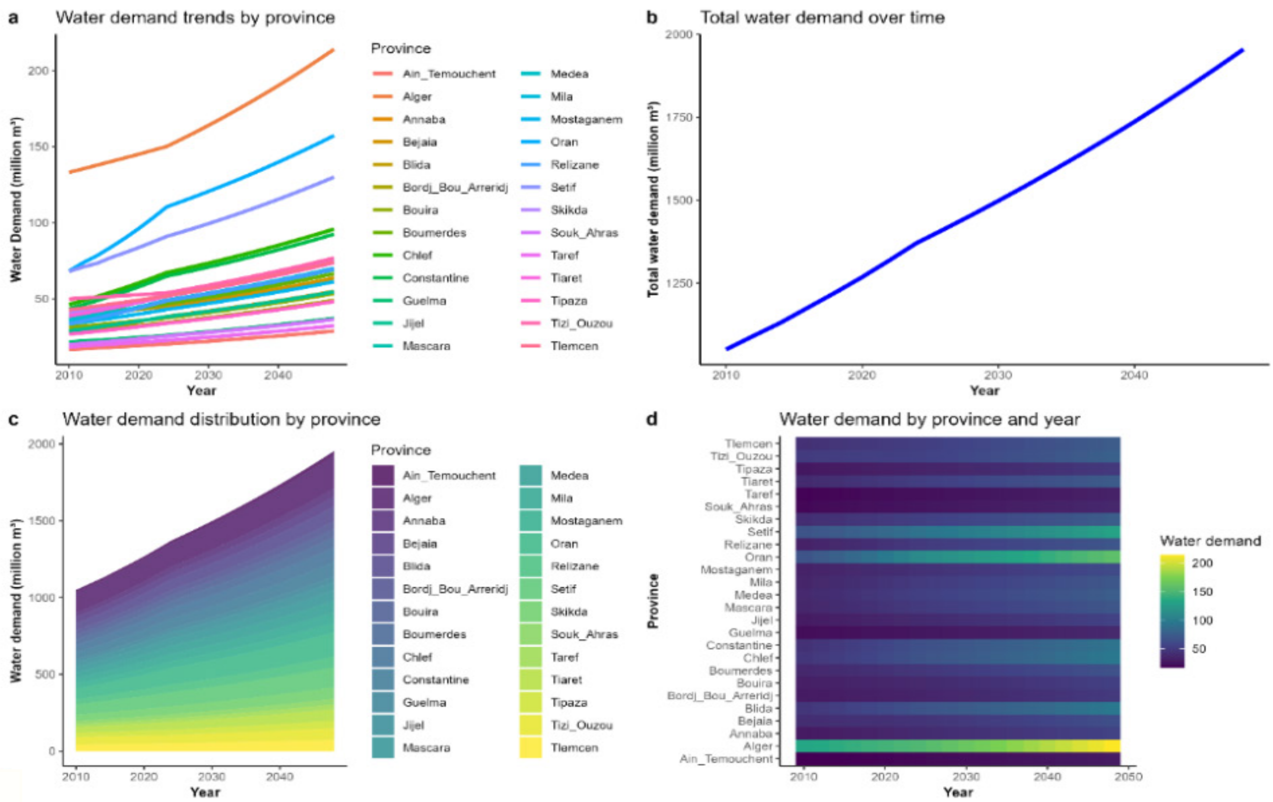



**Figure.4** *Water demand by year and province: a) Water demand trends, b) Total demand of water over year, c) Distribution of water demand showing the contribution of each province to total water demand, d) Heatmap showing the highest and lowest water demand by year and province.*

## *Comparison Between Water Demand and Water Scarcity Vulnerability*

The comparison between water demand and water scarcity vulnerability in Algeria reveals significant correlations between high water demand areas and those with pronounced vulnerability. Between 2008 and 2050, certain provinces like Oran show strong demand growth projected to exceed 260 Mm³, while being classified as having «very high» vulnerability due to population density, increasing industrialization, and limited natural water resources. Other regions such as Setif and other High Plateau provinces also experience high demand and «high» vulnerability, characterized by arid climate and inadequate hydraulic infrastructure. However, some provinces like Algiers show high water demand but moderate vulnerability due to advanced infrastructure including desalination, while Constantine and Annaba benefit from relatively more humid climate and better-structured water networks, reducing their vulnerability. This analysis highlights the importance of investing in water infrastructure, particularly in high-vulnerability regions, to address future water supply challenges in Algeria.

## *Analysis and Discussion of Unmet Water Demand in Algeria (2010-2050)*

The prospective analysis of unmet water demand (UWD) in Algeria reveals significant disparities between coastal and inland provinces, emphasizing structural water management challenges amid growing demographic pressure and climate variability. Projections show coastal provinces will significantly reduce UWD through desalination, with Algiers decreasing from 29.7 Mm³ in 2024 to full coverage by 2026 (Figure 5). Oran shows initial improvement but faces renewed deficits post-2040 (+71.2 Mm³), indicating infrastructure saturation. In contrast, inland provinces like Constantine and Sétif show exponential UWD growth, projected to reach +136.6 Mm³ and +148.9 Mm³ by 2050 respectively ($R^2 > 0.95$), confirming structural water stress. Limited return flows (Constantine: 49.6 Mm³/year; Sétif: 24.8 Mm³/year) and lack of alternatives to desalination exacerbate this trend.

While desalination proves energy efficient for coastal cities, its long-term sustainability beyond 2040 remains uncertain due to rising costs. Persistent coastal-inland disparities validate environmental justice concerns regarding equitable water access. Strategic recommendations include: planned desalination expansion (e.g., new Oran plant by 2035), hybrid solutions for deficit regions (wastewater recycling could cover 40% of UWD), and a national UWD observatory with real-time hydrological simulations.

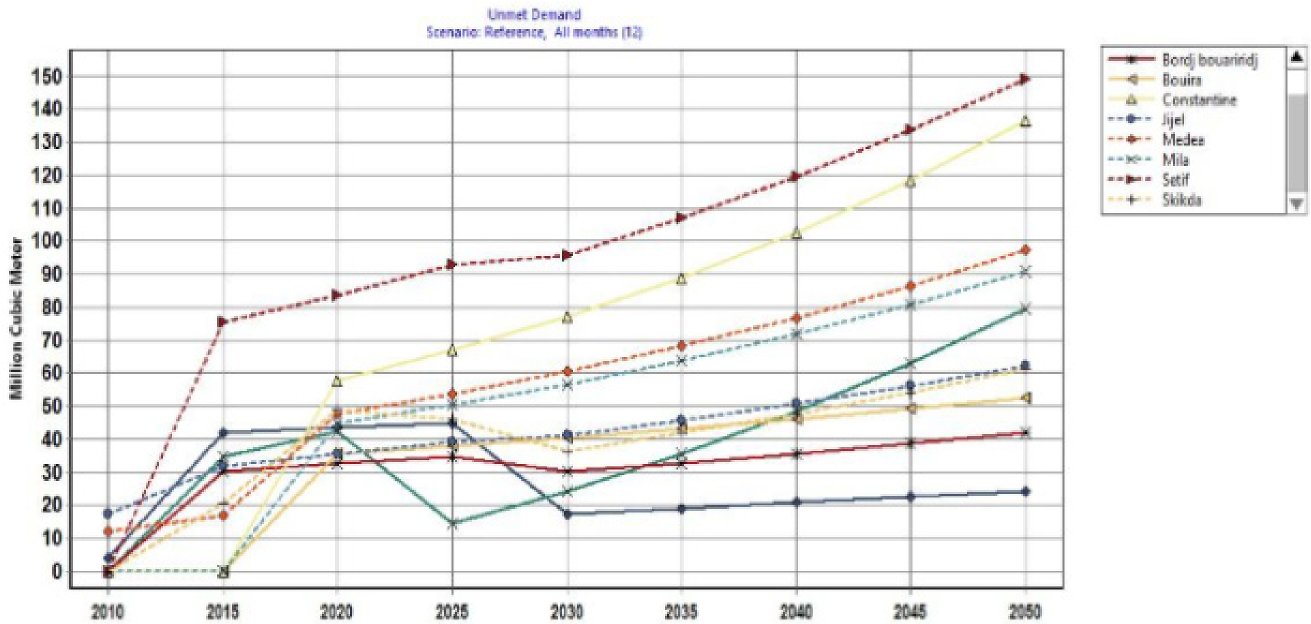



**Figure.5** *Evolution of unmet water demand by province according to the reference scenario (2008-2050).*

The dendrogram from the hierarchical clustering (Fig. 6) classifies provinces into four distinct clusters based on their water demand patterns. Provinces within the same cluster exhibit similar water consumption behaviors, reflecting shared economic, climatic, or demographic characteristics (e.g., Oran and Sétif). This classification supports the development of tailored regional water policies by grouping provinces with comparable needs and challenges. In terms of prioritization, the cluster that includes provinces such as Algiers, Oran, and Sétif is likely the most sensitive to variations in water demand. These provinces are characterized by high population densities and significant urbanization, resulting in elevated and fluctuating water needs. As such, they require quicker and more adaptive management responses to maintain the balance between supply and demand and to mitigate potential shortages. The hierarchical clustering analysis highlights a clear differentiation of provinces based on their water demand profiles. Coastal and metropolitan areas tend to form distinct clusters, separate from more inland or rural regions. This suggests that urban pressure, infrastructure development, and demographic trends are key drivers of water demand behavior, providing a strong basis for targeted and efficient policy interventions.

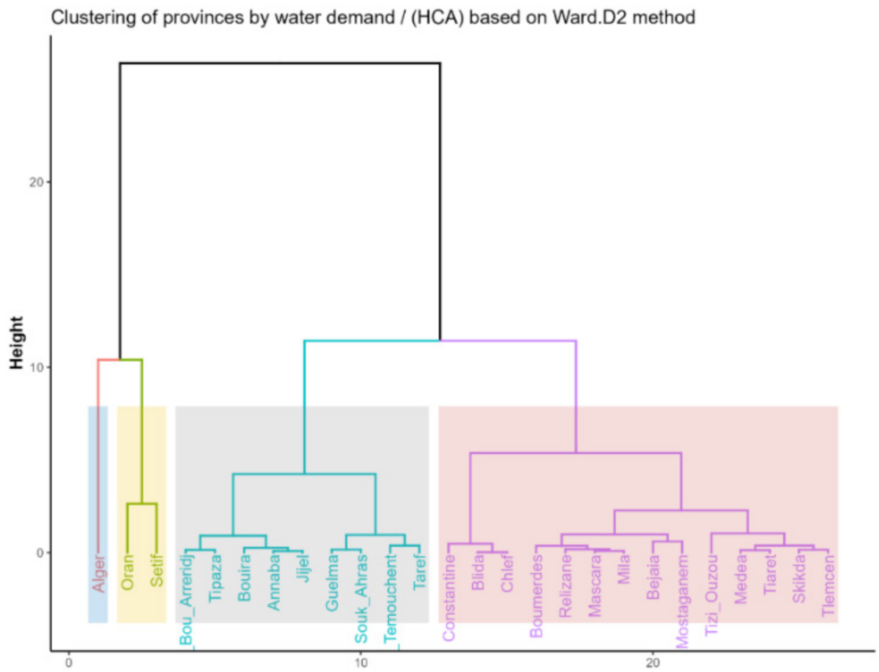



**Figure.6** *hierarchical clustering analysis showing the pairwise dissimilarity between provinces based on their water demand trends over time.*

### *Comparative Analysis of Unmet Water Demand With and Without Desalination (2010-2050)*

The evolution of unmet water demand in major Algerian provinces highlights a significant worsening of water deficit by 2050 in the absence of seawater desalination. Projection analysis reveals increasing pressure on conventional resources, particularly in large urban areas and regions with high population density. Coastal provinces like Algiers and Oran, already under significant water stress, show alarming increases in their unmet demand. Algiers sees its deficit nearly double, reaching over 260 Mm³ by 2050 compared to 140 Mm³ in a scenario including desalination, while Oran increases from 110 Mm³ to 190 Mm³. This trend illustrates these metropolitan areas' growing dependence on alternative water resources to meet rising domestic and industrial needs (Figure 7).

The impact is also notable in inland provinces and the High Plateaus, where water resources mainly depend on dams and groundwater. In these regions, the absence of desalination increases pressure on local resources, exacerbating existing deficits. Blida and Constantine experience strong growth in their unmet demand, exceeding 120 Mm³ and 100 Mm³ respectively by 2050. Similarly, in the High Plateaus, projections indicate marked increases, particularly in Sétif (from 85 Mm³ to 130 Mm³), Bordj Bou Arréridj (from 65 Mm³ to 105 Mm³) and M'sila (from 100 Mm³ to 140 Mm³). These dynamics underscores conventional resources' inability to meet growing demand, worsened by climate variability and population growth.

The comparative analysis of both scenarios highlights the strategic importance of desalination as a resilience and an adaptation lever against water stress. The absence of this technology leads to an average 50 to 100% increase in water deficit depending on the province, with particularly critical impact in large urban areas where unmet demand can nearly double. Simultaneously, increased pressure on conventional resources heightens vulnerability in inland regions, compromising their ability to meet future needs. These results confirm that desalination development, combined with optimized management of water networks and existing resources, constitutes a fundamental approach to ensuring the country's long-term water security.

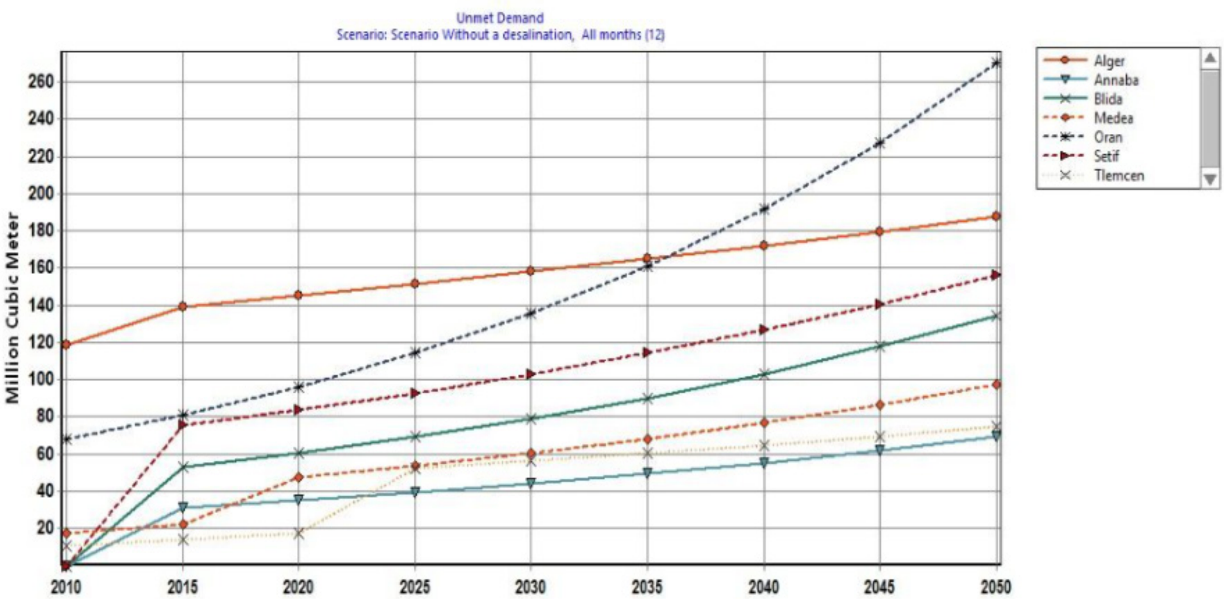



**Figure.7** *Evolution of unmet water demand by province according to the scenario without desalination (2008-2050).*

### *Analysis and Interpretation of Wastewater Return Flows (2010-2050)*

The evolution of wastewater return flows in Algeria between 2010 and 2050 (Figure 8) reveals contrasted spatio-temporal dynamics, highlighting both an overall increase in treated wastewater volumes (+76.9%, from 662.6 Mm³ in 2010 to 1,172.5 Mm³ in 2050) and significant regional disparities. The analysis shows that 63.2% of flows are concentrated in three provinces (Algiers, Oran, Tlemcen), where annual growth rates range between 1.3% (Algiers) and 3.8% (Oran), reflecting differentiated development of sanitation infrastructure.

Examination of time series shows a significant acceleration in water investments between 2020 and 2030, a period during which flows increased by 38.7%, compared to only 12.4% between 2010 and 2020. This phenomenon coincides with the commissioning of new infrastructure, particularly in Tiaret (+15.5 Mm³/year) and Relizane (+42.5 Mm³/year), which show respective increases of +175% and +145% between 2025 and 2035. However, spatial distribution analysis reveals increasing concentration of flows in coastal areas (rising from 4.7 to 8.3 Mm³/year on average), while inland regions remain structurally under-equipped (1.2 to 2.1 Mm³/year).

These results highlight major challenges in water resource management. The strong centralization of flows in major urban centers reflects prioritization of investments towards areas with high demographic and economic pressure, but exacerbates territorial imbalances in sanitation facilities. The period 2025-2035 thus emerges as a strategic turning point for treatment capacity development, requiring trade-offs between consolidating existing infrastructure and expanding into chronically deficient areas.

Operationally, these findings argue for a dual approach. It is imperative to increase capacity in major urban centers to absorb continuously growing water demand, while integrating treated water reuse strategies into agricultural and industrial cycles. Simultaneously, strengthening water infrastructure in inland regions should be prioritized to reduce territorial inequalities and improve overall sanitation network resilience. Enhancing monitoring and data collection systems appears crucial to refine projections and better anticipate flow interruptions. By integrating these elements into coherent national water planning, it would be possible to optimize wastewater management and ensure more balanced resource redistribution by 2050.

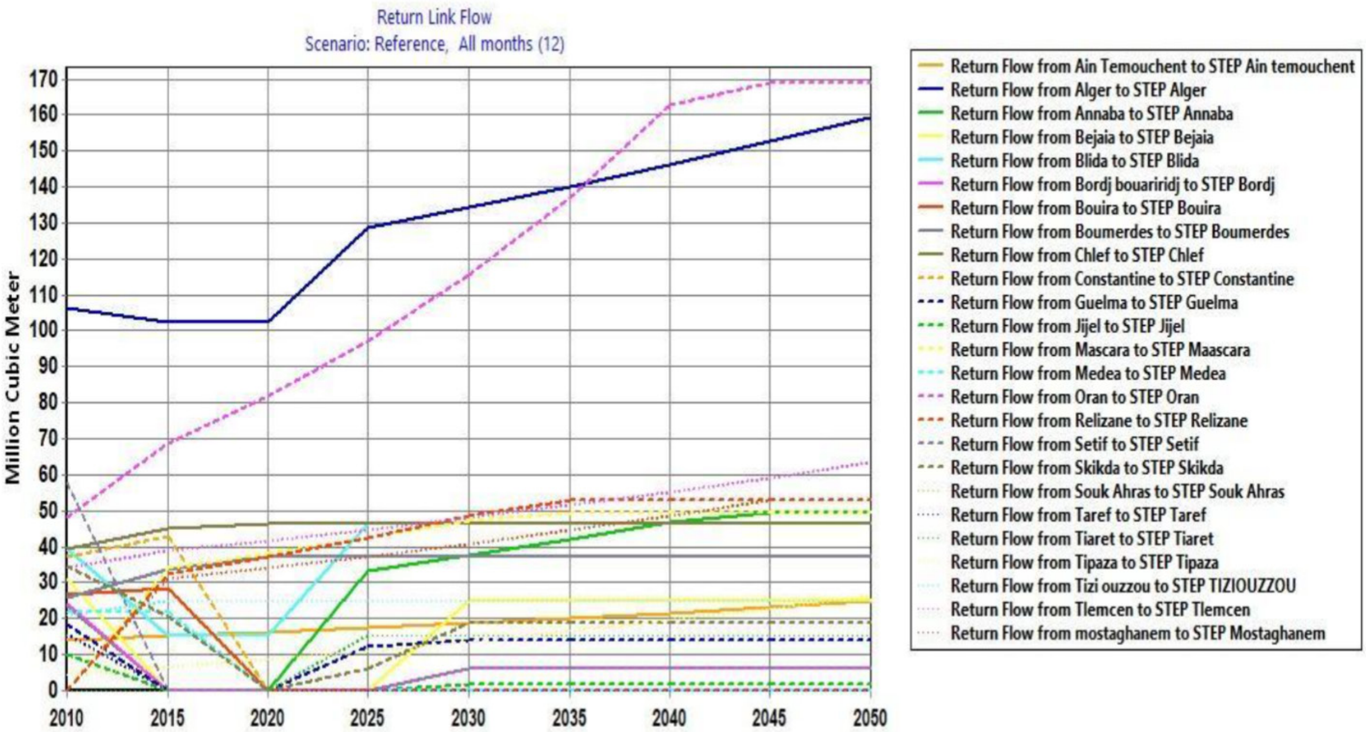



**Figure.8** *Evolution of return flows to treatment plants by province according to the reference scenario (2010-2050).*

Cross-analysis of treated wastewater return flows and unmet water demand (UWD) in Algeria reveals strategic opportunities for more effective water resource management by 2050 projections. According to forecasts, water deficit could reach 368.7 Mm³/year in several provinces, while available treated wastewater volumes could exceed 450 Mm³/year, representing a key lever to reduce water supply tensions. Coastal provinces like Algiers and Oran benefit from significant desalination potential and treated water reuse for non-potable uses, potentially covering over 80% of needs. For example, Oran, with a return flow of 169.1 Mm³/year, could meet up to 42% of its 71.2 Mm³/year UWD if its treatment and distribution infrastructure is optimized according to ISO 16075 standards.

Conversely, high-deficit inland provinces like Constantine and Sétif show critical gaps between supply and demand. Constantine, with 136.6 Mm³/year UWD and limited return flow of 49.6 Mm³/year, could only cover 36% of its deficit through wastewater recycling, thus requiring inter-basin transfers from surplus provinces. Implementing hybrid solutions combining water transfers, intensive recycling, and demand management through progressive pricing and water-efficient technologies could reduce UWD by 30-40% in these regions.

Integrating these strategies into a modeling framework estimates that reusing 60% of return flows could reduce national UWD by 35%, while optimizing required investments. Indeed, such an approach would require less budget, nearly 50% less than the $5.6 billion needed for a strategy relying solely on desalination. Further optimization of the water-energy nexus, by integrating treatment plants with renewable energy production units (biogas), could additionally improve infrastructure efficiency and reduce operating costs.

The example of Oran province illustrates the potential impact of these integrated strategies. Despite desalination use, this province would still show a residual deficit of 71.2 Mm³/year by 2050. However, reusing 70 Mm³/year of its treated wastewater for industrial applications (40%), green space irrigation (30%) and urban cleaning (30%) could save up to 58 Mm³/year of potable water, thus reducing pressure on conventional resources.

Systematic integration of return flows into water planning thus constitutes an essential lever to ensure resilience of Algeria's water system. A regulatory approach imposing a minimum 30% reuse rate in most deficient provinces could accelerate this transition. In the long term, the adoption of artificial intelligence-based technologies and the development of public-private partnerships to finance wastewater reuse infrastructure will play a crucial role in achieving Sustainable Development Goal 6 (SDG 6) on clean water and sanitation. Artificial intelligence enables the improvement of wastewater treatment system performance by optimizing operations, reducing energy costs, and ensuring real-time water quality control (Alprol et al., 2024; Luo et al., 2020; Kurniawan et al., 2024). Furthermore, public-private partnerships appear as essential levers for mobilizing necessary funding, sharing risks, and accelerating the implementation of sustainable infrastructure, particularly in rapidly growing urban areas (Paes Ferreira et al., 2022). The joint integration of artificial intelligence and cooperation mechanisms between public and private sectors is fully aligned with a sustainable transition dynamic aimed at addressing challenges related to water scarcity and sanitation within the framework of the 2030 Agenda.

The proposed scenarios for each province take into account the balance between unmet water demand, available wastewater volumes (return flows), and reuse potential. In Algiers, water demand is already fully covered by 2050, mainly due to existing desalination infrastructure; therefore, it is optimal to simply maintain these facilities. In Oran, a significant unmet demand remains, but the high volume of treatable wastewater justifies a combined strategy of desalination and reuse. Constantine faces a high unmet demand and moderate return flows; the most suitable option is to intensify recycling and consider water transfers from other regions. In contrast, in Sétif, the limited availability of wastewater makes reuse insufficient, and only the implementation of structural projects (such as dams, interconnections, and storage systems) can sustainably meet future needs. Finally, in Annaba, the relatively low unmet demand and considerable return flows allow the deficit to be addressed by optimizing existing wastewater treatment plants, making reuse locally effective without requiring major new investments.

| Province | Unmet Water Demand 2050 (Mm³/year) | Return Flow 2050 (Mm³/year) | Reuse Potential (%) | Optimal Scenario |
|---|---|---|---|---|
| **Alger** | 0 | 159.4 | 100% (already satisfied) | Maintain desalination |
| **Oran** | 71.2 | 169.1 | 42% (possible coverage) | Desalination + Reuse |
| **Constantine** | 136.6 | 49.6 | 36% | Intensive recycling + Transfers |
| **Setif** | 148.9 | 24.8 | 17% | Structural projects |
| **Annaba** | 11.0 | 49.6 | 22% | STEP optimization |

**TABLE 2**
**Optimal Water Management Strategies for Selected Pilot Provinces in 2050**

## RECOMMENDATIONS FOR IMPROVED WATER GOVERNANCE IN ALGERIA

**a- Strengthening Water Governance and Regulatory/monitoring Frameworks**

To ensure efficient and sustainable water management, the establishment of a National Water Authority (ANE) is essential. This institution would be responsible for overseeing and coordinating integrated water resource management at the national scale. Additionally, adopting a real-time monitoring and management system leveraging Geographic Information Systems (GIS) and Internet of Things (IoT) sensors would enable better tracking of water resources and faster response to emerging challenges. Moreover, promoting community engagement in decision-making through regional advisory committees would strengthen participatory governance and ensure that water policies reflect local needs.

**b- Establishment of Specialized Agencies**

To address sector-specific challenges, it is necessary to create dedicated institutions for desalination and wastewater reuse. The National Desalination Water Agency (ANDE) would manage the operation and expansion of desalination plants, ensuring their alignment with regional demands. Similarly, the Wastewater Reuse Agency (AREU) would focus on promoting the safe and sustainable reuse of treated wastewater in agriculture, industry, and groundwater recharge, thereby optimizing resource utilization.

**c- Enhancing Water Resource Management Strategies**

Sustainable management of water resources requires innovative approaches such as artificial aquifer recharge using treated wastewater, which would help maintain groundwater reserves. Additionally, the dredging of silted dams during droughts could restore their storage capacity while also repurposing extracted sediments for eco-friendly construction materials, soil enrichment, and medicinal plant cultivation. Furthermore, constructing new dams and optimizing hydraulic transfers between water-deficient and water-abundant regions would improve water accessibility and reduce regional disparities.

**d- Modernization of Infrastructure and Energy Efficiency**

Upgrading Algeria's water infrastructure is crucial to improving efficiency and reducing costs. Integrating photovoltaic solar energy into desalination plants could significantly lower operational expenses. Likewise, deploying advanced irrigation technologies, such as smart drip irrigation, moisture sensors, and artificial intelligence, would minimize water losses in the agricultural sector. Additionally, modernizing wastewater treatment plants and enhancing the reuse of treated water would contribute to water conservation in both agricultural and industrial applications.

**e- Advancing Hydrological Knowledge and Climate Resilience**

A deeper understanding of Algeria's hydrological systems is necessary for informed decision-making. Conducting comprehensive hydrological studies for each watershed would support better local resource management. Furthermore, the development of AI-driven climate and hydrological forecasting models would help predict and mitigate the impacts of droughts. Establishing hydrological and climate databases would also serve as a foundation for scientific research and innovation in sustainable water management.

**f- Raising Public Awareness and Engaging Economic Actors**

Public engagement and economic participation play a vital role in improving water governance. National awareness campaigns should be launched to promote responsible water use and conservation practices. Additionally, stricter water management standards are needed to curb wasteful consumption in domestic, industrial, and agricultural sectors. Encouraging public-private partnerships (PPP) would also facilitate the financing and implementation of innovative projects aimed at enhancing sustainable water management.

## CONCLUSION

This study highlights the urgency of regulatory reform and an integrated approach to ensure the sustainability of Algeria's desalination sector. Modernization of legislative frameworks, including strict standards for brine discharge management, energy efficiency, and large-scale integration of renewable energy, is essential to reconcile water production with environmental protection. Simultaneously, the reuse of treated wastewater must be systematized to reduce pressure on conventional resources while meeting growing unmet water demand, particularly in arid zones and high-density urban areas.

The use of decision-support tools, such as the WEAP model for simulating future needs and clustering methods coupled with AHP multicriteria analysis for identifying vulnerable zones, would optimize infrastructure planning and more accurately assess water deficits. These approaches must be accompanied by rigorous estimation of unmet demand to adjust investments and avoid structural shortages.

However, these measures will remain insufficient without strengthened national coordination. A comprehensive strategy combining optimization of desalination infrastructure, wastewater reuse, innovative solutions for remote areas, and effective inter-province cooperation proves indispensable. By relying on accurate data and models adapted to local realities, Algeria can enhance its water resilience and address the climatic and demographic challenges of the up-coming decades.

# CHAPTER IV. INTEGRATED APPROACHES AND SOCIO-ENVIRONMENTAL STAKES

Bozcaada, Turkey © epicimages

## Chapter IV Introduction

This final chapter addresses the wide and complex topic of desalination impacts. While these aspects have been extensively documented in previous studies analyzing desalination's negative impacts on Mediterranean ecosystems (notably on marine ecosystems and their exposed fauna and flora) and societies, this chapter adopts innovative integrated approaches to provide more nuanced and actionable insights.

The first paper applies the innovative "One Health" concept to the desalination sector enabling a systematic review of interconnected impacts across human health, marine ecosystems, and technology. Building on an in-depth literature analysis and expert surveys across five Mediterranean case studies (Greece, Spain, Tunisia, Cyprus, and Morocco), this theoretical One Health framework reveals the complex interdependencies that traditional sectoral approaches often overlook.

The second article follows a more quantitative approach, exploring similar impacts through inclusive decision-making processes that balance desalination's economic benefits with environmental preservation and social fairness. With composite methodologies and a dedicated Social Water Inclusive Index tailored to the desalination sector, this research highlights the diverse and context-specific nature of desalination impacts, supporting the need for inclusive policies.
Together, these studies showcase how integrated approaches can transform impact assessments from an exhaustive list of impacts into comprehensive frameworks that support the sustainable and socially acceptable development of desalination in the Mediterranean region.

# TOWARDS A 'ONE HEALTH' APPROACH TO SUSTAINABLE DESALINATION: REDUCING ENVIRONMENTAL AND SOCIAL IMPACTS

AUTHOR : MAHA EL MAHDAOUI


## Abstract

The Mediterranean region faces acute water stress exacerbated by climate change and population growth (Alzahid, 2024) (Novo, 2023). To meet rising demand, countries like Morocco, Tunisia, Spain, and Greece are rapidly expanding seawater desalination capacity. Spain alone operates 765 desalination plants producing about 5 million $m^3$ per day (Novo, 2023), making it the fourth-largest desalinating country globally. Morocco plans to exceed 1 billion $m^3$ of desalinated water annually by 2030 to supply major coastal cities (Alzahid, 2024). These investments promise a new, climate-resilient water source, but also spark questions about sustainability and social acceptability. Desalination remains energy-intensive and costly, with environmental side-effects (brine discharge, chemical use) and socio-economic implications for local communities (Alzahid, 2024).

To address these complex challenges, this study adopts a One Health framework – a holistic paradigm linking human health, ecosystem health, and socio-economic well-being – alongside an analysis of public perception and social acceptability. A One Health approach recognizes that the health of people, animals (including marine life), and the environment are interdependent (WHO). By integrating environmental science, public health, and community perspectives, we provide an expert, data-driven evaluation of desalination in the Mediterranean. The analysis covers technical, policy, and environmental aspects in an integrated manner, with case insights from Morocco, Tunisia, Spain, Greece. Key issues include: (1) the interconnections between desalination technology, marine ecosystems, and human health; and (2) public concerns regarding water quality, cost, environmental impacts, and governance. The goal is to inform policymakers and water experts on how to advance desalination as a sustainable and socially acceptable solution in water-scarce Mediterranean contexts.

## INTRODUCTION

The Mediterranean basin is widely recognized as one of the most climate-vulnerable regions globally, with acute exposure to temperature rise, declining precipitation, and increasing frequency of droughts (IPCC, 2022) (Plan Bleu, 2020). These stressors, compounded by rapid urbanization, demographic growth, and agricultural intensification, are straining conventional freshwater sources such as rivers, reservoirs, and aquifers (UNEP/MAP, 2022). To address growing water deficits, several countries — including Morocco, Tunisia, Spain, and Greece — have turned to seawater desalination as a strategic, non-conventional water source (FAO AQUASTAT, 2023) (IEA, 2023). Spain, for instance, now operates over 700 desalination units, while Morocco has committed to supplying over 1 billion m$^3$ of desalinated water annually by 2030 (ONEE, 2022).

While desalination offers reliability in the face of climatic extremes, it poses unresolved questions regarding long-term sustainability. Reverse osmosis technologies are energy-intensive, contribute to marine salinity alteration and biodiversity risks via brine discharge, and may introduce socio-economic tensions through tariff increases or privatization of services (Voutchkov, 2018) (Sola, 2024) (UNEP/MAP, 2022). Furthermore, health-related challenges have emerged, including the potential for mineral-deficient water if not properly re-mineralized (Barbier, 2021). Social resistance has also surfaced where communities perceive environmental risks or lack trust in institutional governance (Fielding, 2014) (Plan Bleu, 2022).

This paper adopts a One Health framework — a systems-based approach that examines the interdependence between human health, ecosystem integrity, and socio-technical systems (McEwen, 2017) (Machalaba, 2015). Originally developed for zoonotic disease management, One Health has increasingly been adapted to environmental health, infrastructure, and climate resilience contexts (WHO-OIE-FAO, 2022). Rather than treating environmental and social factors in isolation, One Health emphasizes their interlinkages, ensuring that solutions optimize co-benefits across all domains.

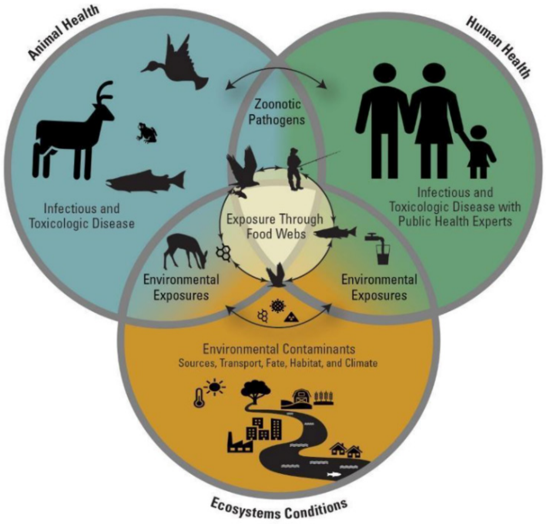



**Figure.1** *One health conceptual diagram (USGS Ecosystems Mission Area , 2023)*

In the Mediterranean desalination sector, this means mitigating ecological harm to protect marine and human health, safeguarding water quality for consumers, and considering socio-economic equity and governance in project implementation.

In parallel, this study incorporates public perception and social acceptability as decisive, often overlooked, dimensions in the success or failure of desalination policies.

By bridging environmental science, health policy, and social analysis, this study aims to critically assess Mediterranean desalination through an interdisciplinary lens. Using both thematic analysis and case-based insights from key regional countries, it seeks to make more resilient, health-protective, and publicly accepted desalination strategies.

## METHODOLOGY

This study adopts an interdisciplinary, qualitative approach to assess the sustainability of seawater desalination in the Mediterranean through the lens of the One Health framework and public perception analysis. One Health, traditionally rooted in zoonotic disease control, is increasingly applied to complex environmental and infrastructure systems where human, ecological, and technological domains interact. It emphasizes the need to assess co-benefits, trade-offs, and feedback loops between ecosystem integrity, human well-being, and socio-technical systems (McEwen, 2017) (WHO-OIE-FAO, 2022). Applied to desalination, this approach enables a systemic understanding of environmental risks (e.g., brine discharge and biodiversity loss), public health considerations (e.g., water quality and nutritional adequacy), and governance challenges (e.g., affordability, transparency, and equity).

Desalination plants inherently bridge the human and natural world, drawing in seawater and returning concentrated brine and chemical by-products to the sea. This creates direct links between water infrastructure and marine ecosystem health. For example, large volumes of seawater intake can entrain and impinge marine organisms, while effluent discharge alters coastal water chemistry (Jones, Qadir, van Vliet, Smakhtin, & Kang, 2019). Any resulting loss in marine biodiversity (such as a decline in fisheries or coastal habitats) eventually feeds back to human communities, affecting food resources, economic livelihoods, and public health. Conversely, the performance and safety of desalination systems are influenced by environmental conditions — algal blooms or source water pollution can disrupt operations and treatment protocols, linking ecological dynamics to engineering outcomes. The One Health lens thus treats desalination, marine ecosystems, and human well-being as a continuum, where disruptions in one domain cascade into others (Destoumieux-Garzón, 2018).

The marine parameters data presented in this study are based on the Mediterranean Sea Physics Reanalysis dataset provided by Copernicus Marine Service-based (CMEMS, 2025) and the climate data is based on the IPCC climate modeling tool, CMIP6 models, specifically using the SSP5-8.5 scenario (IPCC, 2022), which represents a high-emissions pathway.

This interconnected reality calls for integrated, cross-sectoral monitoring and management. Desalination operators must collaborate with marine biologists to monitor ecosystem stress (e.g., changes in indicator species), which may also signal long-term risks to fisheries or recreation. Similarly, public health authorities should coordinate with engineers to ensure health requirements (e.g., mineral content) are embedded into plant design and post-treatment decisions. One Health integration thus requires breaking silos between technical, ecological, and public health disciplines — a shift increasingly recognized as essential for managing complex sustainability challenges (Machalaba, 2015).

In parallel, this study integrates an analysis of public perception and social acceptability, recognizing them as decisive factors in the success or failure of desalination projects. Technically sound and environmentally responsible plants can still falter if public trust or willingness to pay is low. Perceptions of water quality, cost, environmental impact, and institutional transparency heavily influence social uptake. In the Mediterranean, local resistance has emerged in some regions, while in others desalination has been widely accepted — often depending on how governance, communication, and distribution are managed. Understanding and addressing these perceptions is thus critical to securing a broad social license for desalination technologies.

In addition to the literature review and case study synthesis, a survey was administered from April to July 2025 using Google Forms and distributed via social networks and thematic groups in Arabic, French, and Spanish. A total of 60 responses were collected, 15 per country, using convenience and snowball sampling. While the sample is not statistically representative, it provides useful indicative insights into prevailing public perceptions across diverse settings.

The questionnaire was structured around 14 closed-ended questions designed to probe three main dimensions:

- **Perceived necessity of desalination** (e.g., experience of drought, support for desalination, prioritization of alternatives),
- **Public health and environmental concerns** (e.g., worries about safety, quality, and ecological impacts),
- **Governance and trust factors** (e.g., willingness to pay, confidence in regulatory bodies, perception of transparency).

Key findings are presented in Section 4.3.4.

To ground this integrated framework, the paper draws on selected case studies from Morocco, Tunisia, Spain, and Greece,  countries that illustrate contrasting models of governance, energy sourcing, subsidy mechanisms, and community engagement. These cases were purposively selected to highlight contextual differences and shared lessons in applying One Health principles and managing social acceptability. Together, they offer grounded insights into the multidimensional realities of desalination under climate stress.

## RESULTS AND DISCUSSION

### *Environmental dimensions*

### *Alteration of Marine Parameters and Increasing Ecosystem Vulnerability*

The Mediterranean Sea presents distinct spatial variability in key marine parameters that directly influence the environmental footprint of desalination activities. Based on current satellite and model data:

- **Salinity levels** in the Mediterranean Sea are naturally higher than global ocean averages (~35 ppt), ranging from ~37 ppt in the western basin to over 39 ppt in the eastern regions . While brine discharge from desalination has limited influence at the basin scale, its local impact may be significant, especially in areas with already elevated salinity and low water renewal, such as semi-enclosed bays. These localized increases can pose ecological risks to sensitive benthic habitats, reinforcing the need for site-specific assessments and dilution modeling.

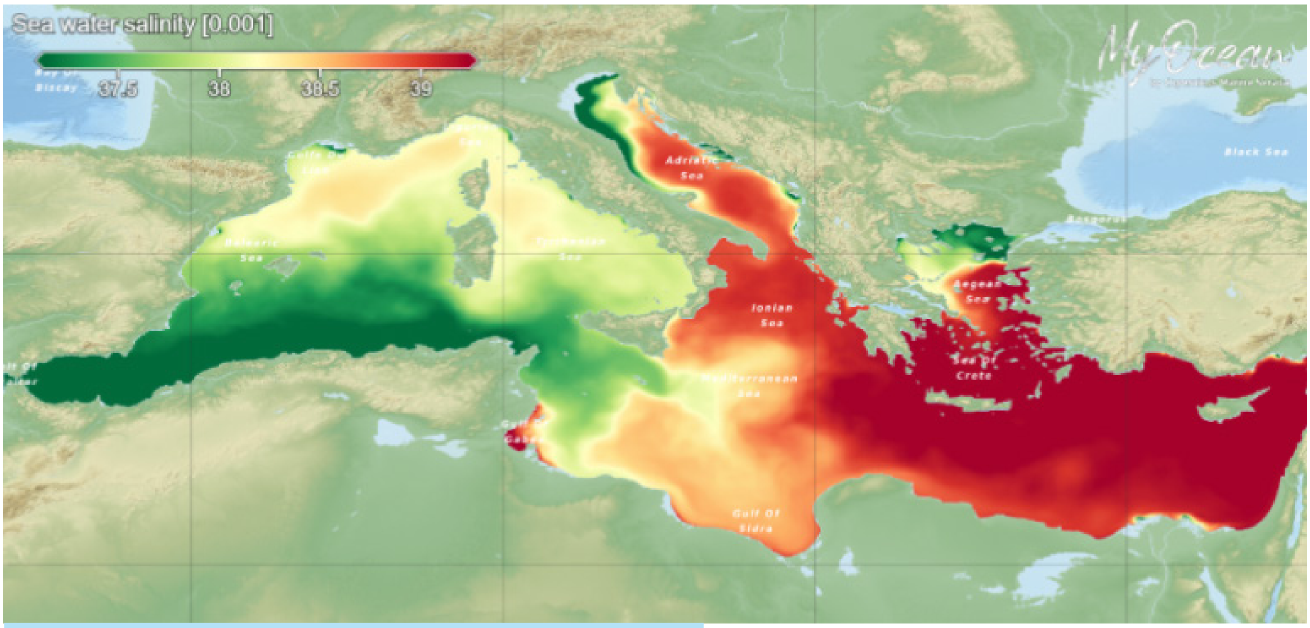



**Figure.2** *Seawater salinity variation map (CMEMS, 2025)*

- Sea surface temperatures (SST) in the Mediterranean range from ~14°C in the northwest (e.g., Ligurian and Adriatic Seas) to above 20°C in the Gulf of Gabes and Levantine Basin. CMIP6 projections under the SSP5-8.5 scenario forecast a 0.5–1°C rise by 2040, especially along the North African coast. While these increases are basin-wide, their interaction with brine discharges is most relevant at local scale, where stratification and reduced vertical mixing can exacerbate the persistence of hypersaline plumes and affect benthic habitats.

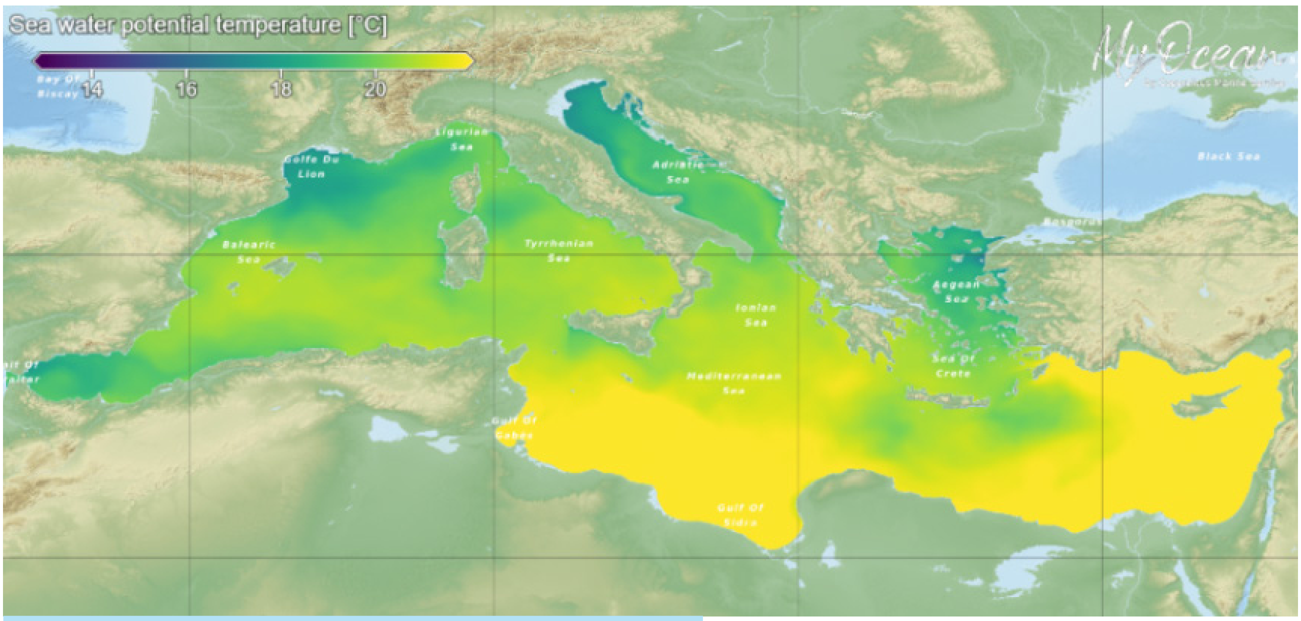



**Figure.3** *Seawater temperature variation map (CMEMS, 2025)*

- Surface pH in the Mediterranean according to CMIP6 projections under the SSP5-8.5 scenario (2021–2040), is expected to decline gradually, particularly in nearshore zones and shallow continental shelves where upwelling processes occur. These areas, which often overlap with desalination outfall locations, are more sensitive to acidification due to limited mixing and biological activity. While deeper offshore waters remain more stable, the near-term acidification of surface layers may incrementally increase vulnerability of benthic organisms and calcifying species. It is important to note that this represents a long-term environmental trend, and that brine discharge from desalination could act as a local compounding factor in areas already experiencing pH decline. This reinforces the need for site-specific monitoring and adaptive management, in line with a One Health approach.

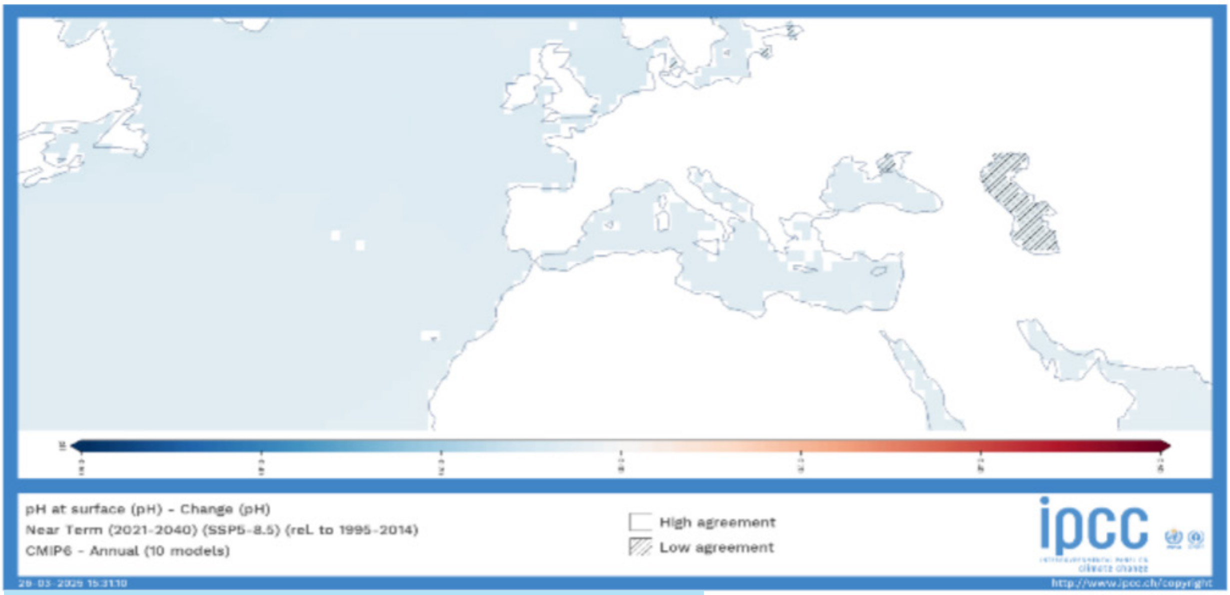



**Figure.4** *pH level change in the near term (2021-2040) according to CMIP6 models, SSP5-8.5 scenario (IPCC, 2022)*

- Current velocity maps show strong eastward and northward currents near the Strait of Gibraltar and Ionian Sea, allowing for greater dilution of brine plumes. In contrast, circulation is much weaker in the central southern basin (e.g., Gulf of Sidra), where brine can stagnate and accumulate

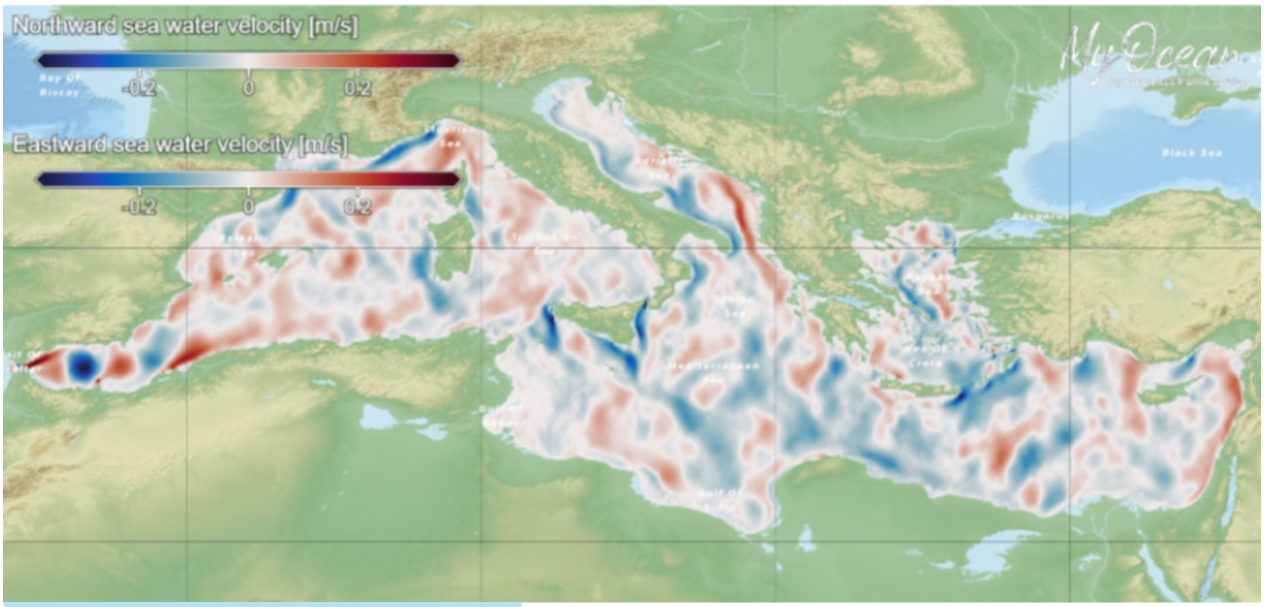



**Figure.5** *Seawater current velocity variation map (CMEMS, 2025)*

These baseline shifts, while not caused by desalination, profoundly affect how ecosystems respond to the additional pressure of brine discharge and thermal or chemical effluents from desalination plants.

Brine discharge, by design, is highly localized and tends to impact salinity, oxygen levels, and temperature in the immediate vicinity of outfalls. In stable or high-energy environments, natural mixing can mitigate these effects. However, under future climate conditions — with warmer, more stratified waters, slower circulation, and reduced wind-driven mixing — the natural resilience mechanisms of these systems are weakened. For example, increased stratification due to warming reduces vertical mixing, making it harder for coastal ecosystems to recover from oxygen depletion or salinity spikes caused by brine. This implies that a brine discharge that may have had negligible impact under past conditions could become ecologically disruptive under future baselines. The risk is particularly acute in enclosed, shallow, or low-energy coastal zones where high SST, weak winds, and limited circulation converge.

Likewise, ocean acidification, while not a direct result of desalination, compounds the vulnerability of calcifying organisms (such as shellfish, corals, and benthic invertebrates) to chemical changes in their habitat. When these organisms are also exposed to hypersaline plumes or temperature anomalies from desalination plants, their physiological tolerance thresholds may be exceeded.

Therefore, environmental impact assessments for desalination should move away from static baseline assumptions and incorporate forward-looking oceanographic modeling. Site selection, diffuser design, and discharge volume thresholds must all be re-evaluated under climate-stressed scenarios. In short, desalination is no longer acting on a stable sea — it's discharging into a shifting system, and that shift must be central to planning and regulation.

### *Biodiversity and Ecosystem Impacts*

Marine ecosystems bear the brunt of desalination's environmental footprint. The by-product brine – water with roughly twice the salinity of seawater plus treatment chemicals – is typically discharged back into the ocean. Research shows that this high-salinity, chemical-laden effluent has negative effects on the surrounding marine environment and its biodiversity (M, H, SA, & Saadaoui, 2022).

The rejection of brine from desalination plants into an already changing marine environment exacerbates stress on marine life and coastal biodiversity. Rising sea surface temperatures can amplify the thermal stress on marine species, while increased acidification weakens the resilience of calcifying organisms such as corals and shellfish. Changes in sea currents and wind patterns influence nutrient distribution and larval dispersion, potentially disrupting ecosystems and fisheries. Brine discharge, characterized by high salinity and potential chemical residues, further compounds these pressures by altering local water chemistry, reducing oxygen levels, and affecting the survival of sensitive marine species. These combined factors create a complex web of environmental stressors that must be carefully considered in impact assessments and mitigation strategies to safeguard marine ecosystems.

Field studies in the Mediterranean have documented biodiversity impacts near desalination outfalls. Species composition shifted, and certain sensitive species virtually disappeared in high-salinity zones, indicating the brine was affecting the base of the marine food web (Kenigsberg C, 2020). Such changes raise concern for broader coastal biodiversity, as benthic organisms are critical for nutrient cycling and as food for larger animals.

In addition to brine, water intake systems can impact coastal fauna. Open-ocean intakes may entrain countless small organisms (eggs, larvae, plankton) and impinge larger fish and invertebrates on intake screens, causing injury or death (UNEP, Mediterranean Plan , 2003). Even with screening (often ~5 mm mesh), entrainment of plankton is inevitable and can measurably reduce local populations, lowering recruitment and overall productivity of the ecosystem (UNEP, Mediterranean Plan , 2003). Over years, continuous plankton losses could affect the food chain, including species important to fisheries. Taken together, these ecological disturbances – if unmitigated – undermine the health of marine ecosystems that coastal communities rely on for food and economic activity. They also contravene the Barcelona Convention's protocols, particularly the LBS Protocol, which regulates pollution from land-based sources such as brine discharge (Annex I), and the SPA/BD Protocol, which mandates the protection of sensitive marine biodiversity and habitats (UNEP/MAP, 2002).

### *Human Health Considerations*

While desalinated water is microbiologically safe and devoid of most pollutants, its purity presents unique human health considerations. Reverse osmosis (RO) – the dominant technology in new plants – strips out nearly all minerals. Desalinated water thus lacks calcium, magnesium, and other minerals essential to human nutrition. If distributed without remineralization, such water can contribute to dietary deficiencies over the long term. In Qatar, a study assessed the mineral content of desalinated bottled water and its potential health implications. The findings revealed that this water type had significantly lower levels of calcium, magnesium, and fluoride compared to non-desalinated bottled water. Consequently, individuals relying primarily on desalinated bottled water may face an increased risk of nutrient deficiencies, as its consumption does not substantially contribute to the recommended daily intakes of these essential minerals for both adults and children. To address this concern, the study recommended implementing cost-effective remineralization techniques to enhance the nutrient content of desalinated water, thereby safeguarding public health (Rowell, Kuiper, & Shomar, 2015). Indeed, remineralization (typically adding calcium carbonate or magnesium compounds) is now considered the best practice for potable desalinated water to protect public health.

Beyond minerals, there are perceptual and potential health issues related to desalinated water quality. Many consumers report that RO-treated water has a flat taste due to its lack of minerals, which can affect public acceptance of drinking it. In Malta, which has relied on seawater RO for decades, residents historically found the tap water "pretty undrinkable" until blending and remineralization practices improved its palatability (Keep Talking Greece, 2024). Taste concerns, while not a direct health threat, can drive people to seek alternative water sources (like bottled water), incurring other economic and environmental costs. Another health consideration is the stability of desalinated water in distribution networks: ultra-pure water can be corrosive to pipes, potentially leaching metals unless treated for stability, though this is manageable with pH adjustment and corrosion inhibitors.

Several countries have already implemented mitigation and water quality control practices to ensure that desalinated water is both safe and socially acceptable (see Table 1 below)

| Measure / Practice | Purpose | One Health Relevance |
|---|---|---|
| **Remineralization (e.g. calcium, magnesium dosing)** | Improve water hardness, taste, and nutritional value | Prevents mineral deficiencies; improves user acceptance |
| **Continuous monitoring of trace contaminants** | Ensure substances like boron and bromate remain below limits | Prevents chronic health risks; ensures regulatory compliance |
| **Adaptation to WHO water quality guidelines** | Align treatment targets with international health standards | Protects population health and builds public trust |
| **Corrosion control (e.g. pH adjustment)** | Prevent leaching of metals from pipes | Ensures safe distribution and infrastructure integrity |

**TABLE 1**
**Measures to Ensure Health-Safe and Acceptable Desalinated Water in the Mediterranean**

### *Socio-Economic and Governance Aspects*

One Health also encompasses the **socio-economic context and governance** of desalination projects, recognizing that human health and environmental outcomes depend on social systems. Desalination in the Mediterranean often involves complex public-private partnerships, significant capital investment, and new institutional arrangements to manage an unconventional water source. Socio-economic factors – such as cost allocation, public trust, and equitable access – can determine whether a project ultimately improves community health and resilience or exacerbates tensions.

A key consideration is the **cost of desalinated water** and who bears it. Desalination produces high-quality water but at a unit cost typically several times that of conventional sources (surface or groundwater). For instance, in Tunisia the current cost to produce 1 m³ of desalinated water is about **3 Tunisian dinars (~$1)**, roughly **three times the cost of reservoir water** (Chibani, 2024). If this full cost were passed on to consumers, water bills would surge. Historically, many governments subsidize desalinated water to keep it affordable – Tunisia's national water company had long sold water to consumers at only a fraction of production cost, covering the rest via state subsidies (Chibani, 2024). However, these subsidies strain public budgets. Tunisia recently had to raise drinking water tariffs by up to 16% in 2024 after years of drought, as the utility could no longer absorb growing deficits (Chibani, 2024). In Morocco, officials estimate desalinated water costs **$0.50–$1.00 per m³**, much higher than traditional sources, raising concerns that poor households may be unable to pay and **inequities in access could widen** (Alzahid, 2024). Thus, the **socio-economic sustainability** of desalination hinges on financial models that balance cost recovery with equity – a One Health approach would emphasize that water affordability is directly tied to community health and economic stability.

**Governance and public engagement** are equally crucial. Because desalination projects often involve foreign companies or private operators (through Build-Operate-Transfer contracts, etc.), questions of transparency and control arise. In Morocco, the drive to privatize drinking water supply via desalination has met resistance. While some welcome desalination as a timely solution, **public acceptance remains mixed due to fears of high costs, environmental harm, and corruption in awarding contracts** (Alzahid, 2024). There have been criticisms that international companies might "manipulate quality and environmental standards" or use undue influence on secure lucrative deals (Alzahid, 2024). Such perceptions underscore a **trust deficit** that can undermine desalination initiatives if not addressed through good governance. A One Health-informed strategy would call for **inclusive decision-making** – involving local communities, ensuring transparency in pricing and operations, and upholding strong regulatory standards – to build trust.

The concept of **social acceptability** in water projects hinges on fairness and trust: communities need to feel that a desalination plant benefits society broadly (not just investors), that its environmental impacts are controlled, and that authorities will safeguard public interest in the long run. Governance measures to support this include clear communication about water quality (to alleviate health concerns), participatory planning processes, and monitoring committees that include community and environmental representatives. In essence, applying One Health in governance means treating community well-being as part of the project's success criteria, alongside technical and environmental metrics. When socio-economic equity and ecosystem health are explicitly valued, desalination can be pursued in a way that reinforces public health and social cohesion, rather than sparking conflict. This integration of social science with technical planning is critical for desalination's long-term viability in the Mediterranean.

## *Public Perception and Social Acceptability*

### *Concerns About Desalinated Water Quality and Health*

One of the first questions consumers ask is, "Is desalinated water good to drink?" Quality concerns range from taste and aesthetic preferences to deeper worries about health effects. Because desalinated water is often described as "too pure," many people notice its lack of taste, or a slight difference compared to mineral-rich spring or well water. For example, early experiences in Malta and Cyprus, which depended on RO desalination, left an impression of flat-tasting water that some locals deemed unpalatable . Proper post-treatment (remineralization) has largely mitigated this issue in modern plants, but the perception can linger that desalinated water is "artificial" or missing something. Educational campaigns can help by explaining that minerals are added for health and taste, and that the water meets all safety standards.
A more serious public concern is whether long-term consumption of desalinated water could have health consequences. As discussed in the One Health section, the primary health consideration is the low mineral content. Public awareness of the magnesium deficiency issue has been growing, especially in countries like Cyprus where most tap water is desalinated . Media reports have highlighted studies linking desalinated water to increased health risks if not re-mineralized. However, it also presents an opportunity: governments and utilities can respond by visibly adopting measures to enhance water with essential minerals, reassuring consumers that the water is not only safe but optimized for health.

Another aspect is the psychological acceptance of drinking water sourced from the sea. Unlike recycled wastewater (which often faces a "yuck" factor), seawater desalination is generally more accepted, as the source (mostly the ocean) is natural and distant from human waste . Surveys in various regions have found people slightly prefer desalinated water over recycled water for drinking, provided they believe its quality is good . The key drivers of acceptance are knowledge and positive perception of the water quality . Therefore, water agencies in Spain, Morocco, and elsewhere have undertaken public information campaigns when introducing desalinated supply – emphasizing that the water is high quality, meets strict standards, and in some cases, even mixing it with conventional water initially to gradually familiarize consumers. Over time, if residents consistently experience clear, odorless, good-tasting water and see health authorities endorsing it, concerns usually diminish. In summary, while quality and health concerns about desalinated water do exist among the public, they can be effectively managed through proper water treatment and proactive communication. Ensuring people understand that their water is safe, healthy, and closely monitored is crucial for social acceptability.

### *Affordability and Willingness to Pay*

Cost is often the most palpable issue for the public. Desalination's expense can translate into **higher water tariffs**, which households and farmers are acutely sensitive to. Public perception in Mediterranean countries reflects a dual reality: on one hand, people value water security and may accept some price increase to avoid severe shortages; on the other hand, there is a limit to what is considered affordable or fair, especially for lower-income groups. If desalinated water is perceived as making water bills "skyrocket," public support can quickly turn into opposition (Alzahid, 2024).

Experience from **Spain's southeast agricultural regions** is telling. In Almería and Murcia, desalinated water was offered to farmers to supplement dwindling aquifers. **Initial acceptance was low** – surveys in Níjar (Spain) found that desalinated seawater had the **"lowest acceptance level" among farmers as a water source, mainly due to its price** (A., Belmonte-Ureña, & & Valera, 2017). Farmers felt the water was too expensive to be economically viable for irrigation, and they were unwilling to pay so much more compared to traditional sources. In addition, because desalinated water is low in minerals, farmers worried they would need to spend more on fertilizer to replace lost nutrients, further raising costs (A., Belmonte-Ureña, & & Valera, 2017). This indicates that willingness-to-pay is closely tied to perceived downstream costs and benefits. Only when subsidies or drought conditions made alternatives impossible did more farmers start using the desal water. The Spanish government recognized this barrier and in 2023 allocated substantial funding to **reduce water tariffs for farmers using desalination**, effectively subsidizing the cost to encourage uptake (Novo, 2023).

In urban contexts, **household water bills** are the focus. Morocco's pursuit of large desalination plants has prompted debates about tariff impacts. Citizens fear that private involvement and high operational costs will lead to **sharp rate hikes for consumers, potentially putting water out of reach for the poo**r (Alzahid, 2024). These concerns are not unfounded – in Tunisia, as noted, water prices are being incrementally raised as desalination increases supply, ending an era of heavy subsidy. In Greece's Aegean islands, where small desal units are often the only solution during summer, locals have complained that **the cost of running desalination for tourist demands has been passed on to residents.** On some islands, water tariffs reportedly doubled for locals in recent years to cover the expense of emergency desalination units, which bred resentment when residents felt they were subsidizing excessive tourist water use (Keep Talking Greece, 2024). This highlights a social acceptability issue of **who pays for desalinated water** – if the cost burden is seen as unjust (e.g. locals paying for hotels' water), opposition grows.

Addressing affordability concerns requires policy interventions. Options include government subsidies for desalination (as practiced in Algeria and historically in Tunisia), tiered pricing structures to protect essential household use, and improving plant energy efficiency to drive costs down. Importantly, communicating the **value proposition** of desalination helps – for example, explaining that without it, the cost of economic losses from water shortage (or the cost of importing water) would be even higher. In drought-stricken Barcelona, authorities justified the high cost of running Europe's largest desal plant by comparing it to the cost of water restrictions or tanker shipments (Novo, 2023). Many residents accepted slightly higher bills knowing it was averting an extreme shortage. Thus, willingness to pay can increase if people perceive desalinated water as **necessary and delivering clear benefits** to them (reliable supply, avoiding crisis) and if measures are in place to keep it **fairly priced**. Engaging with consumers about pricing and perhaps offering lifeline tariffs or subsidies for vulnerable groups, can mitigate backlash. Ultimately, ensuring desalinated water is affordable is not just an economic issue but a social one – it affects equity and the inclusiveness of water access, which is central to public health and welfare.

### *Environmental and Energy Concerns*

Environmental considerations feature prominently in public perception, especially among communities and stakeholders attuned to sustainability issues. While earlier decades saw desalination framed mostly as a technical fix for water scarcity, today many citizens and NGOs question its **environmental footprint – from marine ecosystem damage to carbon emissions.** In the Mediterranean, where environmental awareness is high, these concerns influence the social license for desalination projects.

One major public concern is the **impact of brine discharge on marine life.** Coastal communities, including fishermen, divers, and environmental groups, often voice fears that desalination will "kill the sea" in the vicinity of outfalls. Such fears are not abstract – observations of saline waste harming seagrass beds or altering local water quality have been reported near some plants. For example, in Morocco, media and civil society have highlighted that **concentrated brine effluent can disrupt coastal biodiversity and ecological balance** (Alzahid, 2024). Likewise, Tunisian environmental activists warn that without robust impact studies, desalination could **accelerate ecological collapse in fragile coastal ecosystems** already stressed by pollution (Chibani, 2024). These perceptions put pressure on authorities to prove that new desalination plants will not irreversibly damage marine environments. As a result, some projects face stringent EIA requirements or, in a few cases, public protests demanding relocation of outfalls to less sensitive areas.

Another linked concern is the **energy consumption and carbon footprint** of desalination. People increasingly recognize that while desalination solves water scarcity, it can be very energy-intensive, potentially clashing with climate change goals. In places like Greece's islands, running diesel-fueled desal generators to supply peak summer demand is seen as paradoxical – solving one environmental problem (water shortage) while worsening another (carbon emissions). **Desalination currently accounts for a significant share of the water sector's energy use** (e.g. ~40% of the cost of Tunisia's desalinated water is energy (Chibani, 2024), and if powered by fossil fuels, it contributes to $CO_2$ emissions. Environmental groups sometimes label desalination a "carbon-heavy" solution and urge prioritizing conservation or reuse before resorting to it. For instance, in Spain and Morocco there have been calls to ensure new desalination plants are coupled with renewable energy to reduce their carbon footprint (Chibani, 2024). The Moroccan government has indeed responded by planning wind and solar farms to supply desal plants (such as a wind-powered component for the Agadir desalination facility) (Chibani, 2024). Showcasing these measures can improve public perception by demonstrating a commitment to sustainable operation.

There is also an **eco-justice dimension:** some critics argue that desalination enables unsustainable water use practices (like excessive tourism development or water-intensive industries) under the guise of a technical fix, instead of addressing root causes of scarcity. As noted in a Greek island case, easy availability of desalinated water "encouraged overconsumption" and uncontrolled development, raising concerns that it might be enabling environmentally harmful growth (Journalism Fund Europe, 2025). Communities want assurances that desalination is part of a broader sustainable water strategy, not a license to overuse water.

To bolster public acceptability, project proponents now often emphasize environmental mitigation and **integrated resource management.** They highlight steps like brine dilution techniques, marine monitoring programs, use of green energy, and pairing desalination with water conservation programs. For example, Spain's drought plans combine new desalination capacity with strict water saving rules and water reuse projects (Novo, 2023), sending a message that desalination is one piece of a holistic strategy. Such framing can reassure the environmentally conscious public that desalination is being pursued responsibly. In summary, while desalination's environmental impacts are a source of concern and debate, transparent efforts to minimize harm – and evidence from existing plants operating with minimal ecological disruption – can help in gaining public support. Engaging with environmental NGOs and experts in the planning process can also preempt conflicts and incorporate community knowledge into project design, aligning with the One Health ethos of collaborative, cross-sector solutions.

### *Trust in Desalination Governance and Transparency*

Public acceptance ultimately hinges on **trust** – trust that the water is safe and fairly priced (addressed earlier), and trust that the institutions running desalination are competent and act in the public's interest. In the Mediterranean, water governance has had its challenges, from corruption scandals in utility management to anti-privatization protests. Desalination projects, often high-profile and capital-intensive, tend to magnify existing trust issues or, conversely, become symbols of good governance if managed well. The degree of public trust in those delivering desalinated water can make or break social acceptability.

A frequent source of skepticism is the **role of private companies** and foreign investors in desalination. Because many Mediterranean countries lack domestic desal manufacturing, they partner with international firms (from Europe, UAE, etc.) to build and sometimes operate the plants. In North Africa particularly, there is wariness of ceding control of vital water infrastructure to private hands. **Past experiences of privatized water utilities have left mixed impressions.** In Morocco's major cities, for example, foreign-owned concessionaires (Veolia, Suez, etc.) faced public anger over tariff hikes and service issues, culminating in protests over high bills and even termination of at least one contract (Alzahid, 2024). This history colors how people view new desal PPP projects. Reports that companies won contracts through political connections or offered side deals deepen mistrust (Alzahid, 2024). Thus, even before a desalination plant produces its first drop, **the transparency of the tendering and contracting process** can influence public sentiment. Civil society groups have called for open procurement and accountability to ensure desal projects are awarded on merit and not undermined by corruption. Governments that heed these calls – by publishing contract details, environmental compliance data, and allowing independent audits – tend to foster greater trust.

| Country / Case | Governance Model | Regulatory Oversight | Effect on Public Trust |
|---|---|---|---|
| **Tunisia (past)** | Fully public utility (SONEDE) | Direct state management, low tariffs | Maintained high trust; but led to underinvestment in infrastructure |
| **Tunisia (current)** | Transition to foreign-financed desalination | Need to demonstrate strong regulation of new operators | Public trust fragile; risks backlash if affordability not protected |
| **General mechanisms** | Participatory practices (plant visits, advisory bodies) | Civil society inclusion in oversight and communication | Increases transparency, humanizes the process, improves legitimacy |

**TABLE 2**
**Governance Models and Institutional Oversight in Desalination**

Finally, **communication and responsiveness** are pivotal. People need avenues to voice concerns and get clear answers – whether it's clarity on how tariffs are set or prompt information in the event of any operational incident (e.g. an unscheduled plant shutdown or a minor non-compliance). A governance culture that treats citizens as partners in the desalination endeavor, rather than passive recipients, tends to earn legitimacy. This might involve public forums, publishing annual reports on desalination's performance and impacts, and allowing independent researchers to study and publish findings about the plant's ecological and health effects. In the age of social media, any perception of a cover-up or withholding information can do outsized damage to trust. On the flip side, a well-handled issue – such as swiftly correcting a water quality parameter and openly explaining it – can reinforce trust.

In summary, **social acceptability blossoms where governance is transparent, participatory, and accountable.** Mediterranean desalination projects will gain enduring public support if people believe the institutions behind them are trustworthy. By integrating robust governance measures (as part of the One Health approach's socio-economic pillar), countries can ensure that desalinated water is not just technically successful but socially embraced as a common good.

### *Empirical Insights from Cross-Country Survey*

To complement the conceptual and case-based analysis of desalination in the Mediterranean, an exploratory public perception survey was conducted across four countries: Morocco, Tunisia, Spain, and France. These countries were selected to reflect both North and South Mediterranean contexts with different levels of desalination exposure, governance models, and water scarcity profiles.

### *Key Results*

| Country | % Think Desal is a Good Solution | % Willing to Pay More | % Trust Authorities | % Concerned about Health | % Say Public is Informed |
|---|---|---|---|---|---|
| Morocco | 87% | 10% | 20% | 53% | 15% |
| Spain | 86.7% | 12% | 20% | 53% | 24% |
| France | 53% | 13% | 40% | 47% | 26% |
| Tunisia | 86.8% | 17% | 33% | 67% | 23% |

TABLE 3
**Results from a 60-person cross-country survey exploring social acceptability under a One Health lens (July 2025)**

A detailed analysis of the results revealed several consistent patterns:

- **High perception of drought and support for desalination** was observed in **Morocco, Tunisia, and Spain**, where **86.7% of respondents acknowledged** drought as a pressing issue, and an equal proportion viewed desalination as a good solution. In contrast, **none of the French respondents** reported drought as a concern, and support for desalination was lower **(53.3%)**, reflecting differing hydro-climatic contexts and urgency.
- Despite broad support in principle, **willingness to pay more** for desalinated water was low across all four countries: only **13.3%** of respondents were in favor. This highlights a **price sensitivity** that could pose challenges to project implementation, especially if desalination is positioned as a premium service.
- **Health concerns** emerged as a major theme, with **66.7%** of respondents across all countries indicating some level of worry about the potential effects of desalinated water on their health. Environmental concerns were less prominent (26.7% overall), although **Tunisia showed a slightly higher level (40%)**, possibly reflecting stronger awareness or exposure to brine discharge impacts.
- **Institutional trust and public knowledge** appear to be weak pillars of social acceptability. Only **40%** of respondents expressed confidence that authorities could ensure the safety and quality of desalinated water. Furthermore, a striking **80% believe that the public is poorly informed** about desalination processes and implications — indicating a significant gap in communication and outreach efforts.
- Lastly, 8**0% of all respondents believe that other solutions (e.g., reducing consumption, reusing treated wastewater)** should be prioritized before investing in desalination. This finding reflects a strong latent preference for integrated water resource management and demand-side efficiency, rather than supply-side engineering alone.

### *Interpretation*

These results suggest that social acceptance of desalination is highly conditional. While most respondents support the idea of desalination as a response to climate-induced water scarcity, this support does not translate into unconditional buy-in. Factors such as affordability, transparency, health safeguards, and environmental responsibility strongly influence public attitudes.

For policymakers and project developers, the findings imply that successful desalination deployment requires more than technical reliability, it demands a deliberate engagement with public concerns, incorporation of One Health principles into system design, and participatory communication that builds trust and demystifies the process.

*Case Highlights: Desalination Experiences in Key Mediterranean Countries*

| Country | Key Challenges | Opportunities & Progress | Integration of One Health Principles |
|---|---|---|---|
| **Morocco** | High cost of desalinated water; public resistance to privatization; ecological impact on fisheries | Use of PPPs; major scaling targets; renewable energy integration | Guidelines aligned with Barcelona Convention; renewable-powered plants |
| **Tunisia** | Rising tariffs amid subsidy phaseout; environmental risks to wetlands; limited impact monitoring | National strategy to reach 30% desalinated water; exploring solar desalination | NGO calls for brine valorization; environmental awareness emerging |
| **Spain** | Farmer resistance to cost; energy use & emissions | Strong public communication; co-location with power plants; large-scale investment | Brine diffusion regulations; RE integration & hydrogen pilots |
| **Greece** | Overdependence on desal for tourism; cost inequality; maintenance issues on islands | Community reliance; EU-funded upgrades; tiered pricing reforms | Some use of RE; calls for tourism-water planning; regional coordination |
| **Cyprus** | Initial resistance to cost; rapid infrastructure scale-up | Post-crisis acceptance; city-scale supply now secured | Post-crisis framing as public health security |
| **Algeria** | High tariffs; under-maintained infrastructure | Massive infrastructure network; urban supply in coastal zones | Weak integration; lessons in operational sustainability |

**TABLE 4**
**Comparative Overview of Desalination in Key Mediterranean Countries under a One Health Lens**

### Morocco

Morocco is scaling desalination aggressively, targeting over 1 billion m³/year by 2030. Flagship projects like Agadir aim to supply both drinking and irrigation needs, but public skepticism remains high due to cost (~$1/m³) and reliance on PPPs. Past protests against foreign operators have prompted a return to public water governance. Morocco is actively seeking to green its desalination fleet through renewable energy and has aligned brine disposal with Barcelona Convention guidance, a partial operationalization of One Health principles. Its challenge lies in maintaining affordability and trust while expanding rapidly.

### Tunisia

Desalination now anchors Tunisia's national water strategy, with targets to supply 30% of domestic needs. Projects like Djerba and Sfax show technical ambition, but cost remains a flashpoint: desalinated water is 3x costlier than dam water, and the 2024 tariff hike sparked resistance. The state utility's financial stress collides with affordability concerns. While NGOs have pushed for ecological safeguards and brine valorization, actual environmental integration remains weak. Tunisia's case underscores the financial and ecological balancing act in state-led desalination rollouts.

### Spain

Spain's decades-long experience with desalination shows how public perception can shift from skepticism to strategic reliance. After the 2008 drought, large cities like Barcelona turned decisively to desalination, supported by subsidies and communication campaigns. Farmers initially resisted high costs, but targeted subsidies facilitated adoption. Spain enforces brine discharge regulations and is piloting renewables and hydrogen integration. Its One Health relevance lies in proactive communication, environmental regulation, and gradual social normalization — a governance model worth replicating.

### Greece

On Aegean islands, desalination is both a lifeline and a pressure point. It replaced tanker water for residents but also enabled unsustainable tourism expansion, leading to resentment over pricing and supply prioritization. Technical issues persist on small islands due to limited maintenance capacity. Recent shifts toward RE-powered systems and tiered pricing reflect adaptive policy learning. The Greek case reveals that even technically sound desalination can be destabilizing if not aligned with local equity concerns and spatial planning.

**Cyprus**

Cyprus transitioned from shipping emergency water in 2008 to supplying cities through desalination. Initially controversial due to cost, public support grew after drought impacts became undeniable. This case reflects how extreme events can shift public risk perception, reinforcing desalination as part of a national water security narrative. While explicit One Health framing is absent, the emphasis on climate resilience and public health protection resonates with its logic.

**Algeria**

Despite a large network of desalination plants built to supply coastal cities, Algeria's experience shows that infrastructure alone does not ensure acceptance. Tariffs and poor maintenance led to dissatisfaction, exposing weak customer service and institutional communication. One Health integration remains minimal, and the country's case highlights the critical importance of operational quality, affordability, and responsiveness , not just technical scale, in ensuring social license.

## RECOMMENDATIONS AND CONCLUSION

Desalination in the Mediterranean stands at a critical juncture. As climate change deepens water insecurity across the region, desalination is increasingly viewed as a strategic necessity. Yet, its long-term sustainability hinges on how well we manage its ecological, health, and social impacts. This study, combining a One Health lens and public perception insights, underscores that a more integrated approach, technically rigorous, ecologically sound, and socially accepted, is not only feasible, but imperative. The following priority recommendations are proposed for Mediterranean decision-makers, utilities, and regional stakeholders:

- **Institutionalize One Health into Desalination Planning:** Require health and ecosystem indicators in project impact assessments. Include ecologists and public health experts in project design. Set clear thresholds for brine discharge salinity and ensure post-treatment to WHO standards. Promote the One Health concept regionally via platforms like UfM or the Barcelona Convention, transforming it from academic discourse into applied governance.
- **Engage Communities and Build Public Trust:** Involve civil society and local users from early planning stages. Publicly share information on water quality, pricing, and project impacts. Address fears around taste, cost, or private-sector control with targeted outreach. Use tools like citizen advisory panels, site visits, and feedback mechanisms.
- **Innovate to Reduce Environmental Harm:** Favor renewable energy, energy recovery systems, and brine reuse technologies. Design marine structures (intakes/outfalls) to minimize harm to biodiversity. Monitor environmental effects continuously and disclose results transparently.
- **Ensure Health-Protective Water Quality:** Standardize remineralization and taste optimization for drinking water. Monitor for trace contaminants and conduct epidemiological follow-up where needed. Communicate clearly about water quality assurance to foster user confidence.
- **Ensure Financial Fairness and Viability:** Design balanced tariff structures with lifeline allowances and cross-subsidies. Ensure industrial and tourism sectors contribute proportionally to system financing. Conduct willingness-to-pay studies to align pricing with public acceptability. As costs decline (e.g., through tech improvements), pass benefits to consumers.
- **Integrate Desalination in Broader Water Strategies:** Combine desalination with conservation, reuse, and demand-side management. Communicate its role as part of a diversified water resilience strategy. Link upstream watershed protection to downstream marine protection in planning.

**Implementation Challenges and Next Steps:**

Despite growing momentum, implementing these recommendations will require overcoming structural, regulatory, and financial constraints. Many countries lack clear brine discharge standards, effective cost-recovery frameworks, or cross-sector governance bodies. Public skepticism also remains high in regions with a legacy of privatization or environmental neglect. As a next step, countries should: launch pilot projects that fully integrate One Health metrics; develop regional guidance on social license and ecological safeguards; support multi-stakeholder platforms to co-develop trust-based governance models; and build a shared monitoring infrastructure for cumulative environmental effects. Done right, desalination can support Mediterranean communities in adapting to climate stress without compromising their health, equity, or ecosystems. The challenge is not whether desalination should expand, but how—and for whom.

In conclusion, a **sustainable desalination future for the Mediterranean** will depend on the synergy of advanced technology, enlightened policy, and public engagement. The One Health framework guides us to consider the interdependence of water, environment, and society – ensuring that in solving one problem we do not create others. Public perception, as the barometer of social license, must be monitored and managed with the same diligence as salinity levels or financial costs. The experiences of Morocco, Tunisia, Spain, Greece, and Israel show both the pitfalls to avoid and the best practices to emulate. When desalination is pursued with scientific rigor, ecological caution, and social empathy, it can indeed become a c**ornerstone of water security** in the Mediterranean, enhancing resilience to climate impacts while safeguarding the health of both people and ecosystems. The evidence to date, coupled with ongoing innovations, gives reason for cautious optimism that desalination – done right – can provide a lifeline to Mediterranean communities without compromising the shared environment that binds the region together.

# INCLUSIVE WATERS: ASSESSING THE SOCIOECONOMIC IMPACT OF DESALINATION AND INCLUSIVE DECISION-MAKING IN THE MEDITERRANEAN

AUTHOR : WIDAD METAJER & YKHLEF SOUMIA


## Abstract

Despite the transformative role of desalination in addressing water scarcity, the approach has often prioritised economic efficiency over social equity and environmental sustainability. This proposal explores the socioeconomic impacts of desalination in the Mediterranean, emphasising the importance of inclusive decision-making to balance economic gains with environmental preservation and social equity. To assess the inclusive desalination process, the study constructs a Social Water Inclusion Index (SWII) a novel composite indicator designed to capture multidimensional access to water resources across governance, affordability, and equity domains. Using a dynamic panel dataset for Algeria, Egypt, and Libya from 2000 to 2022, we investigate the complex interplay between desalination expansion, governance quality, and water inclusion outcomes through a Generalized Method of Moments (GMM) model and Dumitrescu-Hurlin panel causality test. Findings reveal that while desalination contributes to improved water inclusion, its effects are conditional on governance performance and remain uneven across countries. Moreover, brine discharge sustainability trade-offs that disproportionately affect socially and environmentally vulnerable populations. The study provides evidence-based insights to inform inclusive, climate-resilient water strategies aligned with SDG 6 and the blue economy agenda.

**Keywords:** inclusive desalination, social water, socioeconomic, GMM, SDG6, SDG10

JEL Classifications: Q25, C33, O13, Q01, H41

## INTRODUCTION AND BACKGROUND: THE EFFECT OF DESALINATION BEYOND MERE ECONOMIC GAIN

Water scarcity is one of the most pressing challenges facing humanity, we live in a water-stressed world. While Earth holds an immense volume of water—approximately 1.4 × $10^9$ $km^3$—only a small fraction is accessible as freshwater, 97.5% of the planet's water is seawater, with an average salinity of 35,000 ppm (milligrams per litre), making it unsuitable for direct human consumption, agriculture, or industrial use (Council et al., 2008; Darre & Toor, 2018; Miller, 2003). The Mediterranean region illustrates this global challenge, indeed, despite being surrounded by vast seas, it faces significant freshwater shortages (Iglesias et al., 2007) due to a combination of factors, including its arid climate, growing population, and increasing water demand from agriculture and tourism (Jacobsen et al., 2012; Laraus, 2004; Yang & Zehnder, 2002). According to the World Bank, Mediterranean countries host only 3% of the world's renewable freshwater resources while supporting over 7% of the global population. These disparities make seawater desalination an essential, albeit resource-intensive, solution for addressing the region's chronic water scarcity (March et al., 2014; Palomar & Losada, 2010; Pulido-Bosch et al., 2019).

Desalination has emerged as a critical solution to this crisis, transforming seawater into potable water and supporting the region's water security. As a cornerstone of the blue economy, desalination is integral to meeting the needs of Mediterranean societies (Borriello et al., 2024; Spalding, 2016). Across the Mediterranean, desalination plants now supply over 3.5% of the region's freshwater, a figure projected to increase as demand outpaces natural replenishment rates. EU funding mechanisms, such as the European Maritime and Fisheries Fund (EMFF), allocated approximately €520 million from 2019 to 2024 to promote desalination innovations, including energy-efficient technologies (Miret Pastor et al., 2024).

However, the rapid expansion of desalination plants often prioritises economic efficiency and utility maximisation, sidelining important social and environmental factors. While the economic gains, such as increased agricultural productivity and industrial growth, are clear, they sometimes come at a cost to local communities and ecosystems (Von Medeazza, 2005). The discharge of brine and other byproducts into marine environments threatens biodiversity (Panagopoulos & Haralambous, 2020), and limited community participation in decision-making worsens social inequalities, especially for those living near desalination facilities (Haddad et al., 2018).

It is imperative to shift the focus of desalination initiatives beyond mere economic utility, sustainable desalination should equally address environmental protection and social equity. Inclusive decision-making can ensure that the benefits of desalination are equitably distributed, and its negative impacts are mitigated (Liu et al., 2022), as shown in Figure (1), implementing sustainable practices for sustainable desalination is crucial to ensure equitable access to water across communities especially the vulnerable portion of society fostering then SDGs 6 (clean water and sanitation) and 10 (reduced inequalities), indeed, inclusive desalination processes emphasise equitable access to water resources, prioritising the needs of marginalised and underserved communities while integrating sustainable practices to minimise environmental impacts.

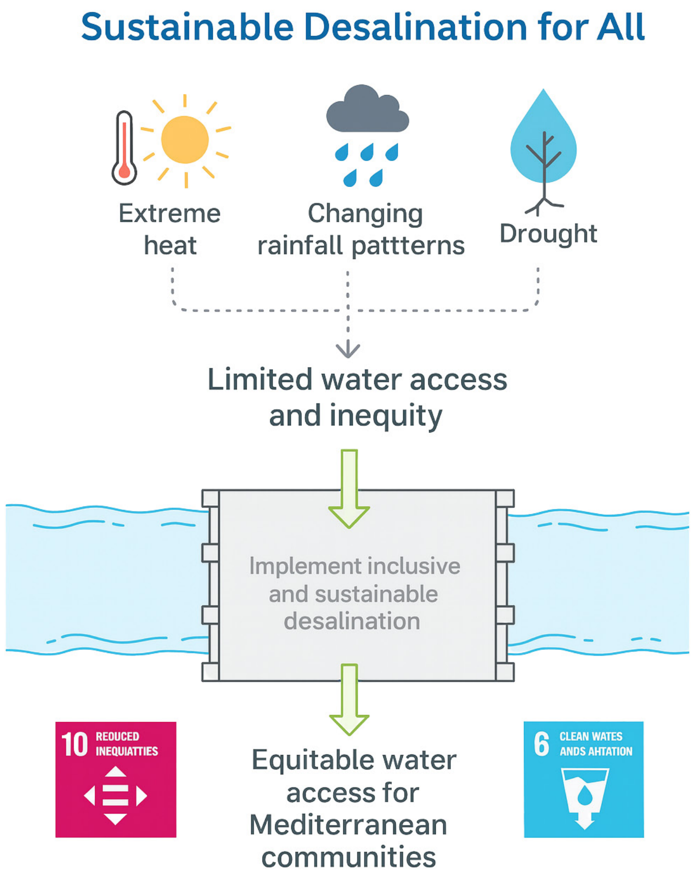



**Figure.1** *Sustainable desalination framework*
*Source: authors' own*

tal, and climate-linked dimensions. At its core, the framework emphasizes how climate pressure manifesting through extreme heat, prolonged drought, and changing rainfall patterns is intensifying water scarcity and inequity in the Mediterranean region. These pressures are driving the expansion of desalination, which, if implemented through inclusive and sustainable approaches, can address these challenges while promoting social equity and environmental sustainability.

The figure shows that inclusive desalination, supported by strong Voice and Accountability mechanisms, is essential to ensure fair access to water and reduce inequalities, particularly for vulnerable and underserved communities. The Social Water Inclusion Index (SWII), developed in this study, serves as a tool to measure the inclusiveness of desalination policies by integrating governance quality, accessibility, and participation.

Environmentally, the framework acknowledges the trade-offs involved: while desalination offers a pathway to water security, its environmental externalities, especially brine discharge, require careful management and innovative circular economy solutions. Although brine valorisation presents a promising avenue, its high energy demands pose additional sustainability challenges. Within the context of the blue economy, oceans are viewed as productive assets—but balancing growth with ecological protection remains complex and politically sensitive.

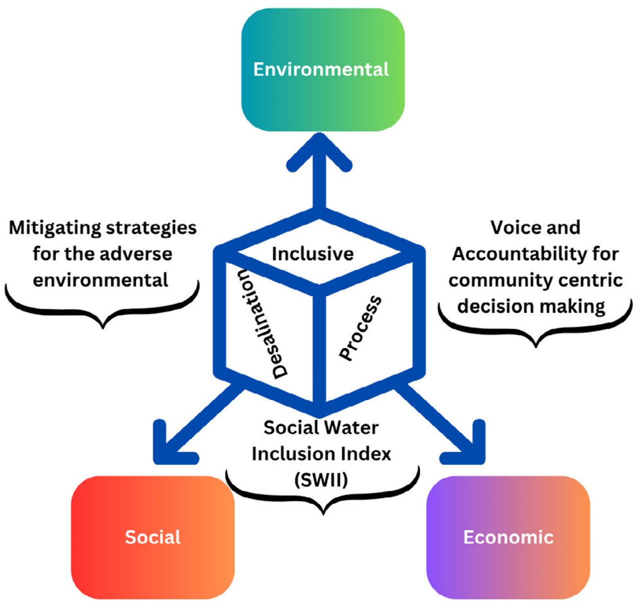



**Figure.2** *The multi-dimensional effect of inclusive desalination*
*Source: authors' own*

This study aims to assess the role of desalination in the Mediterranean by focusing on inclusive decision-making and socioeconomic impact. It will critically examine how desalination can move beyond traditional cost-efficiency models to prioritise equitable resource distribution and social inclusivity. By employing econometric analysis, the research will assess the broader economic and social effects of desalination, exploring pathways to enhance community engagement and ensure fair access to water resources. The ultimate objective is to establish a transformative framework that aligns desalination practices with the principles of the blue economy, fostering resilient and inclusive development across the region.

### *Research added value*

This study addresses critical gaps in existing desalination research by focusing on the overlooked concept of water inclusion, which ensures accessibility, affordability, equity, and public participation in water resource management. Unlike prior studies that emphasize economic efficiency and technological advancements, this research introduces the Social Water Inclusion Index (SWII) as a comprehensive tool to measure and analyze the inclusivity of desalination benefits. By linking water inclusion to Sustainable Development Goals (SDG 6 and SDG 10) and examining governance practices, this study provides actionable insights for fostering equitable and sustainable desalination strategies. Its cross-country analysis in the Mediterranean highlights best practices and challenges, emphasizing the integration of inclusive, transparent governance to balance economic, social, and environmental objectives in water resource management.

## METHODOLOGY

### *Variables selection and data collection:*

This section presents the panel dataset employed to empirically investigate the relationship between desalination activities, environmental externalities, governance quality, and the inclusiveness of water access in three Mediterranean countries: Algeria, Egypt, and Libya. The dataset covers the period from 2000 to 2021, incorporating a combination of original calculations and secondary data from internationally recognized sources.
The structure of the dataset reflects the multidimensional nature of water inclusion, integrating both physical and institutional aspects. Key variables include measures of desalination output and brine discharge, governance indicators (such as Voice and Accountability), water stress levels, and performance on Sustainable Development Goals (SDG 6 and SDG 10).
These variables are summarized in table 01.

| Variable | Description | Source |
|---|---|---|
| **Social Water Inclusion Index (SWII)** | Composite index developed by the authors using PCA, reflecting accessibility, affordability, equity, and participation in desalination benefits. | Constructed using Principal Component Analysis (PCA) – Summarized in section 3.2- |
| **Desalinated water production** | Volume of freshwater produced through desalination processes | AQUASTAT Dissemination System |
| **Brine** | Volume of brine discharged as a by-product of desalination | Calculated based on recovery ratio. Data derived from FAO AQUASTAT, national water agencies, (Methodology detailed in Section 2.2) |
| **The average voice and accountability index** | Measures the extent to which a country's citizens can participate in selecting their government, as well as freedom of expression, association, and media. | Worldwide Governance Indicators, World Bank |
| **Water Scarcity Index (WSI)** | Measures freshwater shortages in each region. WSI scale: values >100% indicate absolute water scarcity | World Resources Institute (WRI), Aqueduct Water Risk Atlas. |
| **Progress on SDG 6 (Clean Water and Sanitation)** | Monitors efforts to ensure sustainable water and sanitation access (e.g., population with improved water access). Composite scoring from 0 (high inequality) to 100 (fully inclusive) | UN SDG database |
| **Progress on SDG 10 (Reduced Inequalities)** | Reflects the reduction of inequalities in water access, affordability, and inclusivity of policies. Composite scoring from 0 (high inequality) to 100 (fully inclusive) | UN SDG database |

**TABLE 1**
**Data and variables**
*Source: by the authors*

Note: SDG 6 and SDG 10 progress are measured using standardized scores ranging from 0 to 100, based on annual indicators of water access, sanitation, and inequality reduction, as compiled by the Sustainable Development Report (Sachs et al., 2023; Pradhan et al., 2017). These scores serve as proxies for the institutional and distributive dimensions of water inclusion.

## *Brine Production Estimation Methodology*

The brine production (also referred as brine discharge) in the context of seawater desalination represents the highly concentrated saline effluent volume which is returned to the marine environment after the extraction and treatment of the freshwater. Hence, it is a liquid discharge related with significant environmental externalities and not an emission in the atmospheric sense. (Panagopoulos & Haralambous; 2020),

In order to quantify the environmental burden caused by desalination activities, this study estimates the volume of brine discharged annually using a mass-balance recovery equation estimates commonly applied in desalination systems. The following formula represents the approach used.

$$V_b = V_p \times \left(\frac{1-R}{R}\right)$$

Where:

- $V_b$ : Volume of brine (in billion cubic meters/year or $m^3$/ year)
- $V_p$ : Volume of permeate/freshwater produced (same units)
- R : Recovery rate (typically 0.30-0.50 for seawater reverse osmosis)

This mass-balance approach is consistent with methodologies presented in (Panagopoulos & Haralambous; 2020), who used the same equation to assess environmental discharges in the Mediterranean region. It is also in line with the broader desalination environmental impact assessment frameworks discussed in Ghaffour et al. (2013) and Von Medeazza (2005).

### *Recovery Rate Assumption*

To improve accuracy, this study applies country-specific recovery rates based on the national share of Reverse Osmosis (RO) technology. RO systems, particularly Seawater Reverse Osmosis (SWRO), typically achieve recovery rates around 0.45 (Ghaffour et al., 2013; Liu et al., 2022). Using data from the Plan Bleu Observatory (2024), we estimate effective national recovery rates as follows:

- Algeria: RO share = 84.2% → R = 0.38
- Libya: RO share = 68.4% → R = 0.31
- Egypt: RO share = 66.5% → R = 0.30

These values were used to compute annual brine discharge per country based on desalinated freshwater output. While still simplified, this approach allows us to reflect technological heterogeneity across the Mediterranean and better estimate the associated environmental externalities (Panagopoulos & Haralambous, 2020; Von Medeazza, 2005).

### *Recovery Rate Assumption*

To capture the multidimensional aspects of inclusive water governance and to reflect the extent to which water access and governance are participatory, equitable and institutionally accountable, this paper constructs a composite indicator namely the Social Water Index (SWII)

Using the **Principal Component Analysis (PCA)**[22]. This approach is a statistical tool widely used to reduce dimensionality and synthesize complex datasets into a single index (Jolliffe & Cadima, 2016).

Additionally, The SWII was built using four core dimensions of water inclusion, selected based on theoretical relevance and data availability:

| Dimension | Water Use Configuration | Policy Focus |
|---|---|---|
| **Governance** | Regulatory Quality<br>Control of Corruption | Worldwide Governance Indicators (WGI)<br>WGI |
| **Participation** | Civic Participation | Varieties of Democracy (V-Dem) Project |
| **Accessibility** | Access to Drinking Water (%) | JMP/World Bank |

**TABLE 2**
**Index dimensions**
*Source: by the authors*

While these indicators are not exclusive to the desalination sector, they are conceptually and practically **relevant for measuring social inclusion in desalination access and governance**. For example, **access to drinking water** reflects the population's ability to benefit from new water supply infrastructure, including desalinated water. Similarly, **civic participation and governance quality** influence how decisions about siting, pricing, and brine management of desalination plants are made — and whether affected communities have a voice in those processes. These dimensions indirectly capture the institutional context in which desalination operates and its inclusivity.

### *The Dynamic Panel Data Model using Generalized Method of Moments (GMM)*

To account for the dynamic nature of social water inclusion and potential endogeneity among key explanatory variables (e.g., desalination and governance quality), this study employs a Dynamic Panel Data Model using a System Generalized Method of Moments (GMM) estimator developed by Arellano and Bover (1995) and Blundell and Bond (1998)The choice of this model is guided by the dynamic nature of the variables under consideration, the potential for endogeneity in the relationships, and the need to capture variations across countries and over time (Cheng & Bang, 2021). It is particularly effective for large samples with relatively few time periods (Islam, 2013).

22 PCA is particularly useful when dealing with indicators that are correlated or conceptually overlapping, as it extracts the common variance shared across dimensions into a principal component.

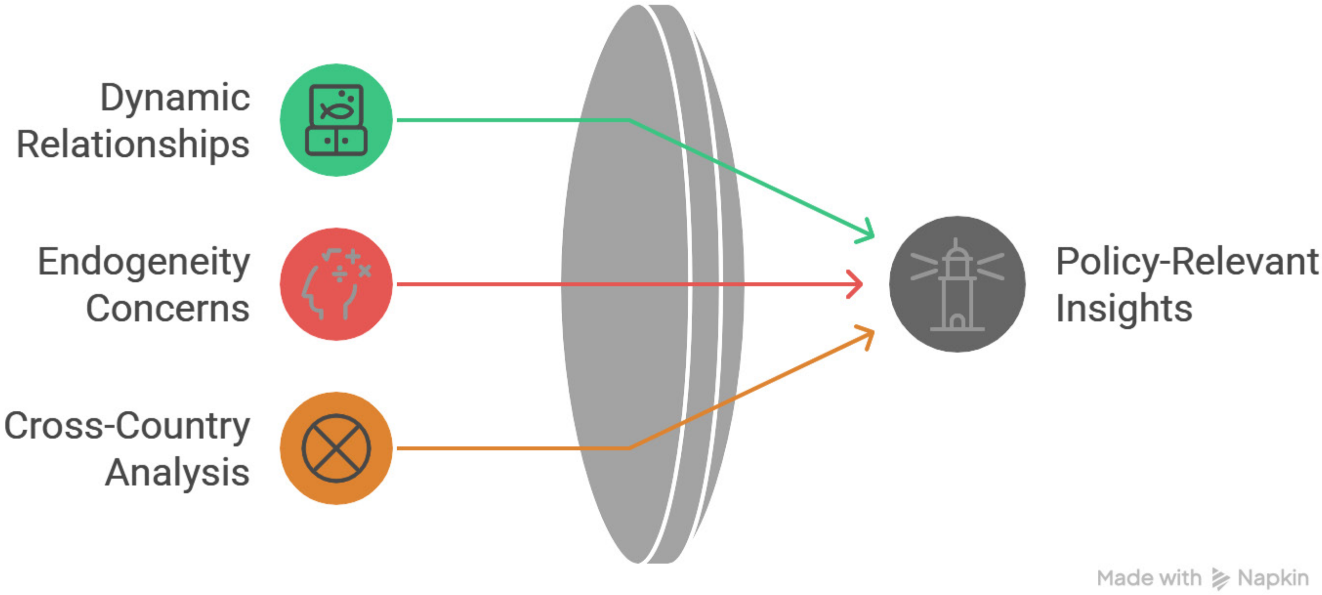



**Figure.3** *benefits of using of GMM in Evaluating Desalination's Socioeconomic Impact*
*Source: authors' own*

Figure 03 shows that using the Generalized Method of Moments (GMM) model to analyze desalination's socioeconomic impact in the Mediterranean may addresses three critical challenges: Dynamic Relationships, by incorporating lagged dependent variables to capture the persistence of socioeconomic outcomes like water affordability and equity over time; Endogeneity Concerns, by using lagged instruments to mitigate biases from feedback loops and unobserved factors like governance quality; and Cross-Country analysis, by leveraging panel data to account for both differences between countries and temporal evolution within them. Together, these components allow GMM to generate policy-relevant insights by providing robust, consistent estimates that inform inclusive and sustainable desalination practices. This aligns with the principles of the blue economy by integrating environmental sustainability with social equity and economic development considerations in the Mediterranean context.

In addition, to investigate the causal dynamics between desalination-related variables, governance quality, and the **Social Water Inclusion Index (SWII)**, this study applies the **Pairwise Dumitrescu–Hurlin (DH) panel causality tes**t (Dumitrescu & Hurlin, 2012). This test is specifically designed for heterogeneous panel data structures, allowing for individual-specific causal relationships across countries, which is particularly relevant for our multi-country Mediterranean sample. The DH test extends the traditional Granger causality framework to panel settings by estimating separate regressions for each cross-sectional unit and aggregating the individual test statistics (W-bar) into a standardized Z-bar statistic. This approach is robust in the presence of fixed T (years) and moderate to large N (countries), and accommodates heterogeneity in slope coefficients and lag structures. It is thus appropriate for detecting causality even when some countries exhibit a relationship and others do not (Ju & Wang, 2023; Lemoine & Tapsoba, 2021). By capturing these cross-country differences, the DH test helps identify whether improvements in governance and progress on SDGs are systematically followed by increases in water inclusion—while allowing for the fact that such relationships may not be uniform across the region.

## RESULTS

This section presents the results of the dynamic panel estimation conducted using the System GMM estimator. The dependent variable is the Social Water Inclusion Index (SWII), while the independent variables capture desalination activity, environmental impact (brine discharge), governance quality, water stress, and progress on SDGs 6 and 10. The model includes a lagged dependent variable to account for dynamic persistence in water inclusion.

### *Social Water Inclusion Index (SWII) Trends in Algeria, Libya, and Egypt*

The Social Water Inclusion Index (SWII), constructed using Principal Component Analysis (PCA), provides a composite score reflecting the multidimensional aspects of water inclusion, including governance quality, civic participation, and access to drinking water. Figure 3 presents the evolution of SWII from 2000 to 2020 for Algeria, Libya, and Egypt, offering insight into the institutional and social inclusiveness of water governance across the three Mediterranean countries.

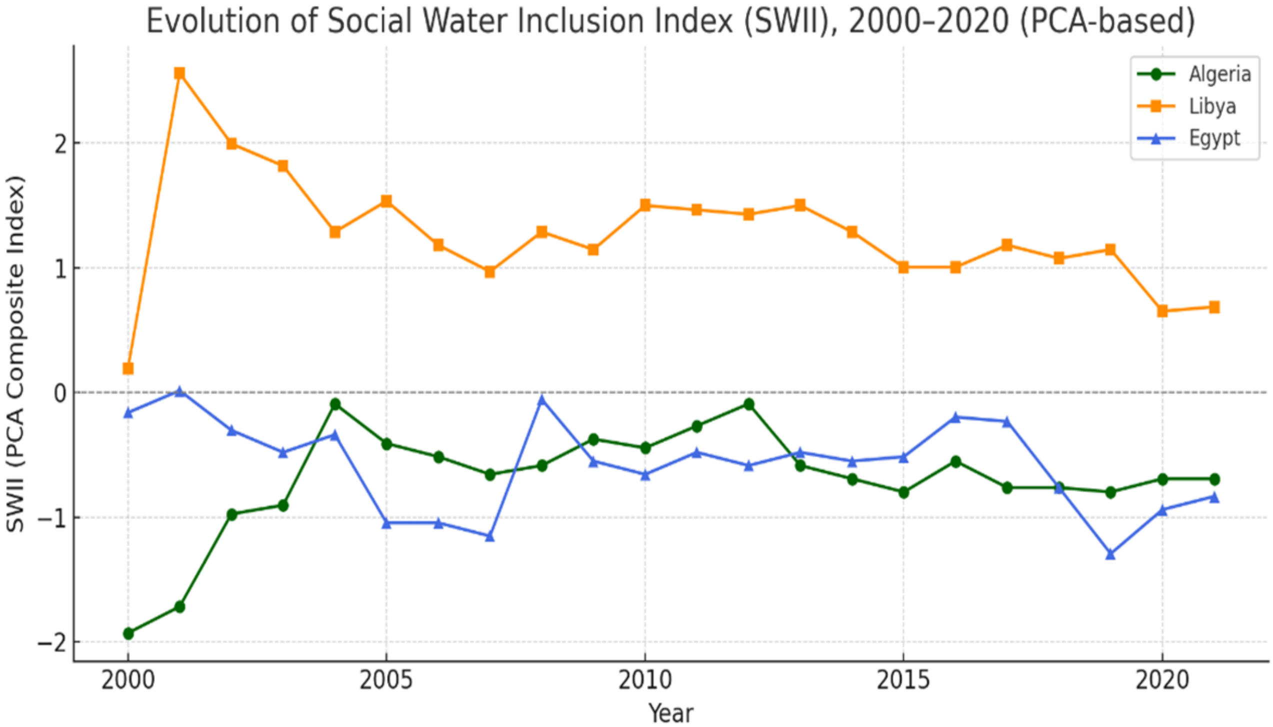



**Figure.4** *Evolution of the Social Water Inclusion Index (SWII)*
*Source: Authors' calculation using PCA-based composite index*

The results reveal substantial differences in the trajectories of SWII values between the countries. Algeria consistently exhibits positive and relatively high SWII scores throughout the period, with a peak around 2001–2002, suggesting strong performance in inclusive water governance, likely driven by public infrastructure expansion and sectoral reforms in the early 2000s. Although some fluctuations are observed, Algeria maintains a steady trend, highlighting relatively stable institutional engagement and access mechanisms. In contrast, Libya displays persistently negative SWII scores, with particularly low values during the early 2000s and only modest improvements thereafter. The trend reflects significant challenges in inclusive governance, likely exacerbated by long-standing political instability, weak civic institutions, and limited community participation in water-related decisions. Despite some recovery after 2010, Libya's SWII remains the lowest among the three countries. Egypt, while also showing negative SWII scores, exhibits a more stable and gradually improving trajectory compared to Libya. This may reflect efforts to expand access to safe drinking water and reform governance, though challenges remain in ensuring participatory mechanisms and equitable distribution. Notably, Egypt's SWII improves slightly in the later years, possibly linked to infrastructure investments and alignment with SDG6 targets.

Overall, the trends suggest that inclusive water governance remains uneven across the region, with Algeria leading in terms of social inclusion, while Libya lags significantly. These disparities highlight the importance of institutional quality and participatory governance in shaping water access outcomes, and reinforce the need for tailored policy interventions adapted to national governance contexts.

### *Data descriptive analysis*

Table (03) summarizes the key descriptive statistics for the main variables in the analysis. These statistics include the mean, median, standard deviation, minimum, and maximum values for each variable. The SWII, which is the dependent variable, is constructed using Principal Component Analysis (PCA) on standardized indicators and hence exhibits a mean near zero and a standard deviation of one. The remaining variables provide insight into the physical and institutional dimensions of water management. Detailed tables with full descriptive statistics are provided in Appendix A.

| Variable | Metrics | Mean | Median | Std. Dev. | Minimum | Maximum |
|---|---|---|---|---|---|---|
| **SWII** | Standardized score | 1.06E-08 | -0.39123 | 1.00000 | -1.92989 | 2.56230 |
| **Brine** | billion m³/year | 0.25717 | 0.17569 | 0.25206 | 0.02078 | 1.04500 |
| **Desalination Production** | billion m³/year | 0.20029 | 0.13080 | 0.20052 | 0.01700 | 0.85500 |
| **VAI** | Unitless (index score) | -0.15409 | 0.16000 | 0.75792 | -1.51000 | 0.66000 |
| **WSI** | % withdrawal over available resources | 105.5842 | 104.4000 | 23.20283 | 66.02000 | 141.1700 |
| **SDG6** | 0–100 scale | 61.94532 | 63.22630 | 2.71230 | 57.28540 | 65.06940 |
| **SDG10** | 0–100 scale | 83.00162 | 83.92850 | 14.54181 | 48.42350 | 97.01500 |

TABLE 3
**Summary Statistics for Key Variables**
*Source: data processing*

The summary statistics indicate considerable variation in the Social Water Inclusion Index (SWII), with values ranging from −1.93 to 2.56, reflecting differences in water governance and access across countries and time. Desalination production (mean: 0.20 billion m³/year) and brine discharge (mean: 0.26) show moderate variability, which likely reflects disparities in investment capacity, technology adoption, and infrastructure coverage. For example, countries with higher desalination capacity may employ more efficient reverse osmosis systems, while others rely on older or intermittent infrastructure, affecting both output and brine intensity. This uneven deployment of desalination technology may also stem from differences in national water strategies and access to coastal desalination zones. The average Voice and Accountability Index (VAI) is negative, suggesting generally weak participatory governance. Water Stress Index (WSI) values exceed 100% on average, pointing to severe overexploitation of water resources. SDG6 scores are relatively consistent, while SDG10 shows broader dispersion, indicating varying levels of social inequality reduction efforts.

## *Correlation matrix*

Before proceeding with the dynamic panel estimation, a correlation analysis was conducted to explore the linear relationships among the key variables in the dataset. The correlation matrix is presented in Table (4).

| Correlation Probability | SWII | BRINE | DESALINATION | VAI | WSI | SDG6 | SDG10 |
|---|---|---|---|---|---|---|---|
| SWII | 1.000000<br>----- | | | | | | |
| BRINE | -0.096318<br>0.4417 | 1.000000<br>----- | | | | | |
| DESALINATION | -0.441288<br>0.0002 | 0.838105<br>0.0000 | 1.000000<br>----- | | | | |
| VAI | 0.578288<br>0.0000 | 0.429377<br>0.0003 | -0.021859<br>0.8617 | 1.000000<br>----- | | | |
| WSI | -0.658080<br>0.0000 | 0.246003<br>0.0465 | 0.621908<br>0.0000 | -0.681640<br>0.0000 | 1.000000<br>----- | | |
| SDG6 | 0.308564<br>0.0117 | -0.783515<br>0.0000 | -0.675352<br>0.0000 | -0.412774<br>0.0006 | -0.054814<br>0.6620 | 1.000000<br>----- | |
| SDG10 | -0.789189<br>0.0000 | 0.399960<br>0.0009 | 0.592683<br>0.0000 | -0.287217<br>0.0194 | 0.604347<br>0.0000 | -0.562038<br>0.0000 | 1.000000<br>----- |

**TABLE 4**
**correlation matrix**
*Source: data processing*

The correlation matrix reveals several noteworthy relationships. The SWII is positively correlated with Voice and Accountability (r = 0.58) and SDG6 (r = 0.31), suggesting a link between inclusive governance, access to clean water, and water inclusion outcomes. Conversely, it shows strong negative correlations with the Water Stress Index (WSI; r = −0.66) and SDG10 (r = −0.79), indicating that higher inequality and water scarcity are associated with lower inclusion. Desalination production is positively correlated with brine discharge (r = 0.84) and WSI (r = 0.62), and negatively with SWII (r = −0.44) and SDG6 (r = −0.68), implying that increased desalination activity may be occurring in more water-stressed and less inclusive contexts.

Overall, the correlations support the hypothesis that governance, environmental stress, and technological interventions jointly shape social water inclusion motivating the multivariate dynamic analysis conducted in the next section.

### *Panel GMM estimation results*

The results of the System GMM model are summarized in Table (5). The coefficient on the lagged dependent variable is positive and highly significant, indicating strong persistence in inclusive water governance.

| Variable | Coefficient | Std. Error | p-value |
|---|---|---|---|
| SWII (lag) | 0.557 | 0.123 | 0.000 |
| Desalination Production | −0.821 | 0.308 | 0.010 |
| Brine | 0.795 | 0.203 | 0.000 |
| Voice and Accountability (VAI) | 0.160 | 0.134 | 0.246 |
| Water Stress Index (WSI) | −0.0045 | 0.0025 | 0.071 |
| SDG6 (Clean Water) | 0.039 | 0.015 | 0.030 |
| SDG10 (Reduced Inequalities) | −0.0125 | 0.005 | 0.045 |

TABLE 5
**GMM Estimation Results for the Determinants of Social Water Inclusion (SWII)**
*Source: data processing*

- Desalination production exhibits a negative and statistically significant effect on SWII ($p < 0.01$), suggesting that while desalination expands supply, it may exacerbate inequality or exclusion if not accompanied by inclusive governance mechanisms.
- Brine discharge, interestingly, shows a negative and significant association with SWII ($p < 0.001$), possibly reflecting infrastructure expansion or stronger regulation where brine output is monitored.
- Voice and Accountability (VAI) has a positive but statistically insignificant effect, suggesting that while governance matters, its influence may be mediated by institutional effectiveness or policy implementation gaps.
- Water Stress Index (WSI) is negatively associated with SWII ($p \approx 0.07$), reinforcing the idea that scarcity undermines equitable access and governance inclusion.
- SDG6 shows a positive and significant effect, confirming the alignment between progress on clean water targets and inclusive outcomes.
- SDG10, contrary to expectations, shows a negative and significant association with SWII, which may reflect short-term trade-offs between macroeconomic inequality policies and sector-specific equity measures.

## *Panel causality results*

Table 06 presents the results of the Pairwise Dumitrescu-Hurlin panel causality tests conducted between SWII and key desalination-related and governance indicators. The findings indicate which directional relationships are statistically significant across the sample.

| Null Hypothesis | W-Stat | Zbar-Stat | Prob | Causality Direction (if any) |
|---|---|---|---|---|
| Desalination Production does not homogeneously cause SWII | 3.1010 | −0.7572 | 0.4489 | No causal relationship |
| SWII does not homogeneously cause Desalination Production | 23.6233 | 2.7753 | 0.0055 | Causality: SWII -> Desalination |
| Brine does not homogeneously cause SWII | 4.8849 | 3.7145 | 0.0002 | Causality: Brine -> SWII |
| SWII does not homogeneously cause Brine | 1.0252 | −0.0986 | 0.9214 | No causal relationship |
| Brine does not homogeneously cause Desalination Production | −1.6E+15 | −1.6E+15 | 0.0000 | Causality: Brine -> Desalination |
| Desalination Production does not homogeneously cause Brine | 1.1899 | 0.0641 | 0.9489 | No causal relationship |
| SDG6 does not homogeneously cause SWII | 1.7906 | −0.3323 | 0.7396 | No causal relationship |
| SWII does not homogeneously cause SDG6 | 4.1328 | 1.1731 | 0.2408 | No causal relationship |
| SDG10 does not homogeneously cause SWII | 2.3056 | −0.5983 | 0.5496 | No causal relationship |
| SWII does not homogeneously cause SDG10 | 4.9807 | 0.6383 | 0.5233 | No causal relationship |
| VAI does not homogeneously cause SWII | 3.3085 | 0.6432 | 0.5201 | No causal relationship |
| SWII does not homogeneously cause VAI | 4.7600 | 1.5762 | 0.1150 | No causal relationship |
| WSI does not homogeneously cause Desalination Production | 10.5101 | 0.5181 | 0.6044 | No causal relationship |
| Desalination Production does not homogeneously cause WSI | 19.8212 | 2.1209 | 0.0339 | Causality: Desalination -> WSI |

**TABLE 6**

**Pairwise Dumitrescu-Hurlin Panel Causality Test Results (2000–2021)**

*Source: data processing*

The Dumitrescu-Hurlin panel causality analysis provides empirical insights into the directional interlinkages among desalination outputs, brine discharge, governance quality, water stress, and the Social Water Inclusion Index (SWII) in the Mediterranean context. This approach, which accounts for cross-country heterogeneity, enables us to evaluate whether systematic patterns of causality exist across countries with diverse institutional and hydro-environmental settings.

### *Desalination and SWII: A Bidirectional Nexus*

The results reveal a significant bidirectional causal relationship between desalination and SWII, indicating that desalination efforts both influence and are influenced by levels of social water inclusion. On the one hand, increased desalination capacity directly contributes to improving water access in water-scarce regions, particularly where traditional sources are insufficient or overexploited (Sanz, Blanco-Gutiérrez, & García-Rubio, 2018). This aligns with previous studies emphasizing the potential of desalination to address physical water scarcity and support SDG 6 (García-Rubio, Guardiola, & González-Gómez, 2015). On the other hand, the finding that SWII Granger-causes desalination suggests that rising demand for equitable and reliable water access—driven by demographic growth, urbanization, or policy emphasis on social equity—can stimulate investment in non-conventional water supply technologies. This feedback reinforces the notion that inclusive water policies and infrastructure expansion are interdependent and must be pursued in tandem (Mehta, Thompson, & Harris, 2022).

### *Brine Externalities and Their Social Feedbacks*

Brine discharge is found to Granger-cause SWII, indicating that environmental externalities associated with desalination can indirectly shape social water outcomes. Unmanaged or excessive brine disposal may lead to marine ecosystem degradation, affecting coastal communities and engendering public opposition to desalination projects (Jones et al., 2019). These findings underline the importance of integrating environmental safeguards into desalination strategies to sustain public trust and maintain service continuity. Conversely, brine discharge does not significantly cause desalination production in the reverse direction. This asymmetry suggests that although brine represents a critical environmental concern, it has not yet emerged as a binding constraint on desalination expansion in most countries—potentially due to weak regulatory enforcement or limited public awareness (Lattemann & Höpner, 2008). However, the absence of a current constraint should not preclude future risks as cumulative impacts intensify.

### *Desalination-Brine Interdependence: A Confirmatory Link*

As expected, desalination is found to causally determine brine generation, validating the physical basis of the mass-balance recovery equation. This confirms the consistency of the dataset and supports the reliability of the constructed brine indicator as a function of country-specific recovery rates. The lack of causality in the opposite direction is logical, since brine is a by-product rather than a driver of desalination activity.

### *Voice and Accountability (VAI): Weak Causal Influence*

The analysis yields no statistically significant causal relationships between the Voice and Accountability Index and other core variables. While governance quality remains conceptually critical to water access and infrastructure equity, its influence appears indirect or lagged, potentially manifesting through broader institutional reforms or cross-sectoral integration (World Bank, 2020). Moreover, limited political will and fragmented governance structures in several countries may explain the absence of a strong signal in the panel analysis.

### *Water Stress and SDGs: Structural Challenges*

Neither the Water Stress Index (WSI) nor the SDG6 and SDG10 scores display significant causal relationships with other variables. This may be attributed to their structural nature and slow-moving characteristics. Water stress reflects hydrological imbalances that evolve over decades, while SDG indicators are composite and updated annually, limiting their sensitivity to short-term dynamics. These indicators, though essential for benchmarking, may not capture granular or immediate responses to policy or infrastructure changes (UN-Water, 2021; Sachs et al., 2022).

## DISCUSSION

The GMM results show a significant negative relationship between desalination and the Social Water Inclusion Index (SWII) (-0.82, P-value = 0.0006). The results suggest that an increase in desalination activities is related to a decrease in social water inclusion. Our findings contrast with the expectation that desalination would enhance water access and inclusion. The finding may imply that current desalination methods in the Mediterranean region are not effectively addressing social equity matters, which has been reported extensively in the literature (Cappelletto et al., 2021; March, 2015; O'Neill, 2020; Williams, 2022). For instance, March (2015) and Swyngedouw and Williams (2017) found that desalination projects in Spain and other Mediterranean countries often prioritise technological solutions over social equity considerations. We also have the high costs of desalination infrastructure, which might explain the negative relationship, which can lead to increased water prices and potentially exclude economically disadvantaged populations from accessing this water source (Barak, 2012; Ziolkowska, 2015).

It is important to note that estimating brine volumes in desalination processes is highly sensitive to the chosen recovery rate, which varies depending on the technology used. To address this, our study avoids using a uniform average rate and instead calculates country-specific recovery rates based on the national dominance of reverse osmosis (RO) technologies. According to data from Plan Bleu (2024), RO makes up 84.2% of desalination capacity in Algeria, 68.4% in Libya, and 66.5% in Egypt. Consequently, we applied tailored recovery rates of 0.379, 0.308, and 0.299 respectively—derived from these shares—to estimate brine discharge more accurately for each country. This method improves the credibility of the environmental burden assessment by recognising that RO systems typically have recovery rates between 35–50%, whereas thermal technologies can have much lower values. The variability emphasises the importance of considering brine impacts not only by volume but also by technology type and location conditions (Panagopoulos & Haralambous, 2020; Liu et al., 2022). These refinements ensure that our environmental analysis aligns with real-world practices and technologies used in the Mediterranean desalination sector.

The voice and accountability index (VAI) shows a positive but non-significant relationship with the SWII (0.15, P-value = 0.246). While the findings align with the assumption that better governance leads to improved water inclusion (Allen et al., 2006; Rogers & Hall, 2003; Wei et al., 2018). The lack of statistical significance suggests that other variables may be more important in affecting social water inclusion. Tortajada and Joshi (2013) point to the importance of good governance in water management for achieving equitable outcomes; however, in our study, the non-significant results might be due to the weak link between accountability and SWII in the Mediterranean compared to other factors such as water provision and accessibility.

Our environmental impact as measured by the Brine variable shows a strong negative relationship with SWII ( -0.79, P-value = 0.000). Our result aligns with existing literature on the environmental and social impacts of brine disposal from desalination plants (Ahmed & Anwar, 2012; Belatoui et al., 2017; Fernández-Torquemada et al., 2019, Plan Bleu , 2024). Roberts et al. (2010) stressed on the possible negative effects of brine discharge on marine environments, which can naturally impact the coastal communities reliant on these ecosystems for their livelihood. Indeed, higher Brine production may lead to larger environmental degradation on coastal ecosystems, potentially negatively influencing fishing and tourism industries that many Mediterranean communities rely on, notably Egypt and Algeria. Similarly, the increasing production of Brine requires managing larger volumes of brine, thus leading to higher operational costs for desalination plants, potentially resulting in higher water prices and reduced accessibility for economically disadvantaged populations (Karagiannis & Soldatos, 2008; Zhou & Tol, 2005; Ziolkowska, 2015). Given the structure of our SWII, the negative relationship with Brine is not a surprise. concerns about the environmental impact of large-scale plants, brine discharge and ecosystem disturbance are often perceived negatively by the public, as Fuentes-Bargues (2014) discussed, negative public perception of desalination plants, relatively linked to worrying about brine disposal, can lead to decreased social approval of these projects, potentially affecting water access and inclusion.

Furthermore, the water scarcity index WSI shows a negative relationship with SWII (0.004, P-value = 0.071), which refers to the very difficult task of sustaining inclusive water access in increasing scarce water countries, which is in line with the literature, indeed, a study by Iglesias et al. (2007) reported the challenges of managing water resources in water-scarce Mediterranean regions. Looking at the progress of the SDG6 (Clean Water and Sanitation) we find a positive and significant relationship with SWII (0.038, P-Value = 0.015), this is consistent with the global agenda set by the United Nation and supported by extensive scholarship (Aman et al., 2024; Lele, 2017; Mattos et al., 2021; Puertas & Marti, 2023; Rajapakse et al., 2023). On the other hand, the small but negative and significant relationship between SDG10 indicator (Reduced Inequalities) and the SWII ( -0.012, P-value = 0.039 is more complex. This finding might reflect the challenges identified by Luh et al. (2017), who argue that marginalized communities often reliant on less resilient technologies face a higher risk of water insecurity exacerbating social and health inequalities during the climate crisis. The authors suggest that targeted interventions in the water sector might be necessary to complement general inequality reduction strategies.

## CONCLUSION

The analysis reveals the complex interplay between desalination, governance, environmental factors and social water inclusion in the Mediterranean region. The findings highlight the need for a more holistic approach to water management that considers not only technological solutions but also social equity, environmental sustainability and good governance practice. The policy recommendations presented offer a roadmap for a more inclusive and sustainable approach to desalination in the Mediterranean. By prioritising inclusive governance, integrating social equity metrics into project evaluations, investing in sustainable brine management and developing a regional framework for water governance, Mediterranean countries can transform their approach to desalination. These measures have the potential to address water scarcity and enhance equity.

### Policy recommendations

It is a complicated task per se to standardise the approach to water management in our case of the inclusive waters approach in the Mediterranean. Each country in the Mediterranean region has its national approach and view of its water management, desalination and equity. Also, a study was done by Argemí Ribalta (2022) and it reports that national politics in Euro Mediterranean countries consistently stood in the way of building a shared regional approach to water governance in the Mediterranean. Countries in the region seem unwilling to adopt such a framework, mainly because they want to uphold control over their water resources. There is also an apprehension that enlarging governance to the regional level could make things more problematic, notably given the current absence of adaptable, context-sensitive regional guidelines. While the Union for the Mediterranean (UFM) has made several efforts to coordinate water-related actions, this study suggests that it may not be the right institution to lead such an initiative. In a governance scene strongly shaped by national benefits, a different kind of state-backed institution might be better suited to take on that role. Our investigations on the desalination's socioeconomic impact suggest the need for a paradigm shift in how desalination projects are implemented and managed. The following policy recommendations are designed to address the most pressing challenges.

- Implementing an inclusive governance framework for desalination projects: creating a nationalised/ regional protocol to include marginalised populations, especially communities living in coastal areas, in the decision process of activities and operations of the desalination plants.
- ntegrating social equity metrics into the evaluation process of desalination projects: trough including a feedback mechanism in the form of a quantifiable metric such as SWII index or another similar metric (based on the right regulatory framework of the country/region if applicable) would reflect the social and participatory side of the projects, if the metric is included into pre (approval) and post (feedback) plants implementation, the approach would reflect the environmental and social impact study of the projects, policy makers might establish threshold (min/ max) value to assess the inclusivity of the projects hence, it viability from an environmental and social perspective.
- revising and improving the actual practice of brine management: policymakers might allocate budgets to research and innovation in brine management to coordinate the efforts in the Mediterranean region, especially in the context of the circular economy.

# CONCLUSION

Desalination Plant © tifonimages

Based on the previous research, it is clear that there is a strong water paradox in the Mediterranean represented by an accentuated water demand while natural resources are decreasing with great heterogeneity with regards to the different mediterranean regions. Even if the desalination sector is still controversial, it's an essential adaptation technology in face of water scarcity contexts. However it implies significant challenges. Also, the findings highlight a significant space for sustainable development. Actually, these ten scientific studies move beyond problem cataloging to evidence based sustainability frameworks applying at different scales from international to local areas. One key element to bear in mind is that desalination is a complex socio-technical system that intersects climate, economics, environment and social equity. Therefore, each paper contributes to a critical piece to sustainable implementation understanding with relevant national focus.

Before entering into the complexity of the desalination production system and related socio-economic contexts, it's important to confront the sector with regional stakes and how the Mediterranean desalination sector contributes to international standards. The quantitative modelling and spatialized analysis of Dr. Sari-Hassoun demonstrates the interconnection between desalination and SDG6 objectives in face of environmental trade-offs. On the other hand, how desalination experts and water related experts are experiencing the sector ? Their perceptions are the baseline of the current opportunities and challenges to address. Dr. Mohammed Assaf revealed that such perceptions are significantly heterogeneous and often country and site specifics, same for the solutions, there is no universal or ideal solution to achieve sustainable desalination. Therefore, through his actor perceptions analysis, it reveals gaps between technical solutions and social acceptance. These potential solutions have been also addressed in the third paper by M. Firas Marsit which has demonstrated the importance of regulatory frameworks in the potential development of green solutions, tailored to the desalination sector in the Mediterranean basin.

A central aspect of the scientific effort lies in economics. Desalination sustainability won't be achieved without sustainable economic development models. But concretely, what does it mean ? Economic drivers of desalination must be tackled across the entire desalination lifecycle, considering not just GDP and water prices, but demographics, energy costs, and water demand. This statement is supported by the two first papers proposed by Dr. Samir Maliki, Mourad Kertous and their team of researchers. But the econometrics analysis goes beyond this first core idea, the desalination sector should trigger circular economy transformation with other sectors in order to reduce socio-environmental and economic expenses. The study proposed by Dr. Hadjer Boulila provides strong evidence on how the desalination sector could benefit from such circularity, in this case by exploring the interconnection between desalination and agriculture. The collective insight is clear, economic sustainability for desalination requires integrated approaches that go beyond classical cost-benefit analysis.

The desalination sector doesn't operationalize in a vacuum, it requires clear and declinable regulatory frameworks and associated governance measures. With her regulatory and spatial assessment for Algeria, Dr. Najet Aroua reveals that there are clear gaps between the desalination sector and spatial planning and its urbanization tools, notably in coastal areas where urbanization rates are the highest. Coastal desalination must align with territorial planning. We need integration into water management plans and urban planning for all time horizons, with better regulation of outfalls protecting marine ecosystems. On the other hand, water resources management tools such as the one proposed by Dr. Imad Eddine Bouznad and his team should be further implemented Mediterranean wide. They clearly demonstrate the potential impacts on different Algeria water demand by 2050 when integrating unconventional water resources, at provincial level. These quantitative scenarios show strategic and sustainable integration potential for desalination and wastewater reuse sectors in a more pronounced water stress context.

Last but not least, the sector requires integrated and innovative approaches  such as the One Health concept that has been applied to the sector in the study proposed by Dr Maha El Mahdaoui. By applying the groundbreaking 'One Health' concept to desalination - systematically reviewing interconnected impacts across human health, marine ecosystems, and technology, the findings reveal complex interdependencies that traditional sectoral approaches miss entirely. On top of these holistic visions, the socio-environmental impacts must be apprehended. With the final study of the report, Dr. Widad Metadjer proposes a composite index that provides practical policy tools supporting social equity and cross sector impacts. This study is a starting point in the development and dissemination of social equity assessment metrics, tailored to the desalination sector.

The pathway forward requires moving from controversy to collaboration—embedding these four pillars into Mediterranean desalination practices. This transition demands:

- Policy Innovation: Regulatory frameworks that integrate desalination planning with broader territorial development strategies
- Technological Integration: Adoption of innovative technologies including green hydrogen, advanced brine management, and circular economic models
- Stakeholder Engagement: Inclusive processes that address social acceptability and ensure equitable access to desalination benefits
- Cross-border Collaboration: Regional approaches that leverage Mediterranean countries' diverse experiences and contexts

The research presented in this volume demonstrates that sustainable desalination can play a significant role in Mediterranean water security strategies, while acknowledging that implementation challenges extend beyond technological considerations to encompass governance, economic, and social dimensions. Rather than viewing desalination through a controversial lens, the evidence suggests that integrated approaches combining innovation, regulatory alignment, and inclusive planning can create pathways toward solutions that balance water security with environmental stewardship.
While this collection establishes important analytical foundations, it also reveals the need for continued research and collaborative dialogue. Future investigations might explore long-term monitoring and scaling-up of innovative technologies, cross-regional comparative studies, and the development of adaptive governance frameworks that can evolve with changing Mediterranean contexts. The complexity of sustainable desalination implementation calls for ongoing partnership between researchers, policymakers, and communities to refine approaches and share lessons learned across the region.

The pathway toward sustainable desalination remains a work in progress, requiring continued evidence-based research, stakeholder engagement, and adaptive management strategies that can respond to the diverse and evolving needs of Mediterranean countries.

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## SUSTAINABILITY IN DESALINATION: ADDRESSING RISKS AND MITIGATION STRATEGIES ACROSS THE MEDITERRANEAN REGION – MOHAMMED N. ASSAF

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## ASSESSING THE ECONOMIC VIABILITY OF DESALINATION IN SELECTED MEDITERRANEAN COUNTRIES: HOW CAN IT CONTRIBUTE TO A SUSTAINABLE FUTURE ? – MALIKI SAMIR. B, HILMI NATHALIE, KERTOUS MOURAD AND BENGAHLEM ABDELHADI.

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## BALANCING ACCESS AND SUSTAINABILITY: ASSESSING THE ECONOMIC, SOCIAL, AND ENVIRONMENTAL IMPACTS OF WATER DESALINATION IN ALGERIA – KERTOUS MOURAD, MALIKI SAMIR.B AND SOUR OUIEME

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## CAN DESALINATED WATER DRIVE AGRICULTURAL GROWTH IN ALGERIA ? A FEASIBILITY STUDY FOR THE ECONOMIC AND SUSTAINABLE DEVELOPMENT – HADJER BOULILA, SEYF EDDINE BENBEKHTI AND SALAH EDDINE SARI HASSOUN


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# ANNEX

## EXAMINING THE CONNECTIONS BETWEEN WATER RESOURCE SCARCITY, DESALINATION AND CLIMATE CHANGE: A STUDY SUPPORTING SDG 6 IMPLEMENTATION -SALAH EDDINE SARI HASSOUN, SEYF EDDINE BENBEKHTI, HADJER BOULILA

Table 4 demonstrates that, with the exception of LnSDGSC, none of these series exhibit a normal distribution since their Jarque-Bera probabilities are less than 0.05. Additionally, the CSD of these variables is confirmed by BP-LM and PCD.

| Endogenous Variables | LnSDG | LnSDGW | LnSDGS | LnSDGFR | LnSDGSC |
|---|---|---|---|---|---|
| **$x^2$** | 66.124*** (0) | 65.172*** (0) | 60.197*** (0) | 13.291*** (0.001) | 4.578 (0.101) |
| **BP-LM** | 1064.717*** (0) | 2537.702*** (0) | 3483.296*** (0) | 1779.808*** (0) | 1017.728*** (0) |
| **PCD** | 20.82*** (0) | 10.116*** (0) | 17.465*** (0) | -1.292 (0.196) | 22.06*** (0) |
| **Exogenous Variables** | LnDSL | LnFLK | LnGHG | LnGDP | LnWUI |
| **$x^2$** | 457.520*** (0) | 29.995*** (0) | 7.358** (0.025) | 26.888*** (0) | 1185.746*** (0) |
| **BP-LM** | 2544.032*** (0) | 3100.493*** (0) | 1570.144*** (0) | 1986.316*** (0) | 362.136*** (0) |
| **PCD** | 48.283*** (0) | 18.314*** (0) | 4.746*** (0) | 23.308*** (0) | 10.534*** (0) |

TABLE 4
**Normality and CSD test**
*Note: "***", '**', '*' refer to the significance level at 1, 5 and 10%. (.) refers to probabilities.*

The results of the panel unit-root test, also known as the CIPS test, are displayed in Table 5 following confirmation of the data's evidence of CSD. It shows that LnSDG, LnSDGSC and LnWUI are stationary at the level with I(0), while LnSDGS, LnSDGFR, LnDESAL, LnGHG and LnGDP are stationary at the first-difference (first-order integrated) with I(1), but LnSDGW and LnFLK are not stationary.

| Endo variables | without trend | with trend | decision | Exo variables | without trend | with trend | decision |
|---|---|---|---|---|---|---|---|
| | Zt-bar stat | | | | Zt-bar stat | | |
| **LnSDG** | -2.22** (0.013) | -1.342* (0.09) | I(0) | LnDESAL | -0.136 (0.446) | -0.068 (0.473) | I(1) |
| **d(LnSDG)** | -9.907*** (0) | -7.91*** (0) | | d(LnDESAL) | -5.521*** (0) | -5.558*** (0) | |
| **LnSDGW** | 1.259 (0.896) | 4.673 (0.999) | Non-stationary | LnFLK | -5.004*** (0) | -1.262 (0.103) | Non-stationary |
| **d(LnSDGW)** | 2.899 (0.998) | 5.132 (0.999) | | d(LnFLK) | -1.584* (0.057) | 0.006 (0.502) | |
| **LnSDGS** | -2.461*** (0.007) | 2.582 (0.994) | I(1) | LnGHG | 1.344 (0.910) | -0.838 (0.201) | I(1) |
| **d(LnSDGS)** | -1.470* (0.071) | -2.58*** (0.005) | | d(LnGHG) | 9.788*** (0) | -7.606*** (0) | |
| **LnSDGFR** | -0.918 (0.179) | 0.162 (0.564) | I(1) | LnGDP | 1.007 (0.843) | 0.575 (0.717) | I(1) |
| **d(LnSDGFR)** | -5.518*** (0) | -4.499*** (0) | | d(LnGDP) | -4.990*** (0) | -3.550*** (0) | |
| **LnSDGSC** | -2.749*** (0.003) | -2.217** (0.013) | I(0) | LnWUI | -4.492*** (0) | -3.587*** (0) | I(0) |
| **d(LnSDGSC)** | -9.821*** (0) | -7.63*** (0) | | d(LnWUI) | -11.80*** (0) | -10.25*** (0) | |

**TABLE 6**
**Panel Unit-Root test (CIPS test)**
*Note: "***", '**', '*' refer to the significance level at 1, 5 and 10%. (.) refers to probabilities.*

The model diagnostics for the fixed effect panel model are displayed in Table 6. The results indicate that the residuals do not follow a normal distribution ($x^2$), and there is CSD (BP-LM and PCD). Additionally, the results show that slope heterogeneity exists throughout the model at the 1% level, failing to provide adequate evidence of slope homogeneity (P-Y and B-W).

| Variables | LnSDG | LnSDGW | LnSDGS | LnSDGFR | LnSDGSC |
|---|---|---|---|---|---|
| **BP-LM** | 862.20*** (0) | 1369.43*** (0) | 1852.76*** (0) | 1262.22*** (0) | 676.576*** (0) |
| **PCD** | 5.045*** (0) | 0.738 (0.46) | 3.217*** (0.0013) | -1.342 (0.18) | 15.891*** (0) |
| **$x^2$** | 909.96*** (0) | 4163.36*** (0) | 5.60* (0.06) | 3.30 (0.192) | 105.849*** (0) |
| **P-Y** | 12.434*** (0) | 13.1*** (0) | 23.70*** (0) | 20.232*** (0) | 12.719*** (0) |
| **B-W** | -3.671*** (0) | -4.675*** (0) | -4.421*** (0) | -4.096*** (0) | -2.703*** (0.007) |

**TABLE 7**
**The model diagnostics of the fixed effect panel model**
*Note: "***", '**', '*' refer to the significance level at 1, 5 and 10%. (.) refers to probabilities.*

# SUSTAINABILITY IN DESALINATION: ADDRESSING RISKS AND MITIGATION STRATEGIES ACROSS THE MEDITERRANEAN REGION – MOHAMMED N. ASSAF

**Annex 1 – Detailed Description of Suggested Adaptation Strategies**

This annex provides an in-depth overview of the six adaptation strategies identified and evaluated in the study. Each strategy includes a summary of its key components, technical measures, and relevance to mitigating specific environmental and social impacts associated with desalination activities in the Mediterranean region.

**1. Source Water Intake Mitigation**

Source water intake mitigation strategies focus on minimizing environmental impact by implementing low intake velocity and multi-size mesh screens to prevent organism entrainment. Intake systems are designed with larger openings and mesh coverage, while offshore and underground intakes, including beach wells and infiltration galleries, are encouraged to reduce ecosystem disruption. The use of power plant cooling water as feedwater decreases land use and chemical requirements. Sensitive marine areas are avoided, and barriers such as nets, velocity caps, and bypass systems control intake flow. Protective measures include sealing techniques for aquifers, trench-covered pipelines, and optimized intake locations to prevent habitat disturbance. Subsurface intake systems, such as infiltration galleries and vertical wells, reduce marine species entrainment and chemical pretreatment needs, though their adoption is limited by cost and site feasibility.

**2. Brine Discharge Mitigation**

Brine discharge mitigation involves several key strategies to minimize environmental impact. Advanced brine treatment techniques reduce waste volume, recover freshwater, and lower pollution, while biodegradable and non-toxic chemicals help limit contamination. Reuse and recycling efforts focus on extracting valuable minerals, salts, and freshwater from rejected brine. Multiport diffuser systems enhance dilution and control salinity plumes, and Minimum/Zero Liquid Discharge technologies maximize water recovery while reducing brine output. Optimal outfall locations prevent ecological disruption, and computational modeling tools improve discharge design for effective diffusion. Additionally, green antiscalants and eco-friendly corrosion inhibitors minimize chemical pollution.

**3. Energy Use Mitigation**

The mitigation strategy for Energy Efficiency and Decarbonization in desalination focuses on transitioning to hybrid renewable energy systems (solar-thermal, wind, and wave-powered desalination) to reduce fossil fuel dependency. It emphasizes energy recovery devices (ERDs) such as pressure exchangers and turbines to lower energy consumption in reverse osmosis. Next-generation membranes (e.g., graphene oxide and aquaporin-based) are proposed to enhance efficiency and reduce fouling. The integration of smart water networks with IoT sensors enables predictive maintenance and demand forecasting. Additionally, waste heat recovery from power plants and industrial facilities is suggested to drive thermal desalination. High-efficiency pumps, variable-speed systems, and optimized processes further contribute to reducing overall energy demands and greenhouse gas emissions.

**4. Site selection**

The mitigation strategy for site selection emphasizes minimizing environmental and social impacts by prioritizing locations that protect biodiversity, prevent groundwater contamination, and support effective brine dilution. Key measures include selecting sites away from residential and coastal areas, ensuring proximity to water distribution networks to reduce energy use, and assessing oceanographic conditions to limit marine exposure to contaminants. The strategy also considers minimizing interference with recreational, commercial, and conservation activities while ensuring ecosystems and sensitive species remain unaffected. Proper pipeline sealing is recommended to prevent groundwater contamination, and sites should have sufficient capacity to dilute and disperse brine effectively.

**5. Socio-Economic & Community-Based Mitigation Strategies**

A comprehensive mitigation strategy for enhancing community acceptance of desalination projects includes proactive engagement with local communities through awareness campaigns on freshwater access, job creation, and sustainable desalination practices. Ensuring local employment opportunities via hiring and training programs fosters economic benefits. Stakeholder consultations, including fishermen and policymakers, facilitate inclusive decision-making and address environmental concerns. Additionally, public awareness initiatives and participatory governance promote transparency, while coastal livelihood compensation programs, such as aquaculture and ecotourism, support affected fishing communities, ensuring socio-economic resilience.

**6. Integrated Water Resource Management**

A comprehensive water security and integrated resource management strategy should complement desalination with sustainable practices. Key measures include coupling desalination with Managed Aquifer Recharge (MAR) to store excess freshwater and prevent land subsidence, promoting decentralized and modular desalination plants to reduce environmental and energy impacts, and integrating water reuse through wastewater recycling and stormwater harvesting. A circular water resource management approach involves combining desalination with treated wastewater reuse for irrigation and industry, aquifer recharge to mitigate over-extraction, and rainwater harvesting for non-potable applications. Additionally, integrating seawater desalination with wastewater reuse creates closed-loop water systems, while brine pre-treatment using wastewater sludge helps reduce the environmental impact of desalination brine discharge.

Table A2. Relative weights of desalination impact sub-criteria across six Mediterranean countries (Spain, Greece, Israel, Libya, Algeria, and Tunisia), as assessed by expert respondents. The table presents country-level scores for each sub-impact under the six main impact categories

| Desalination Impacts (Main Criteria) | Problems caused by Desalination Impact (sub-criteria) | Relative weight | | | | | |
|---|---|---|---|---|---|---|---|
| | | Spain | Greece | Israel | Libya | Algeria | Tunisia |
| Marine Ecosystem Damage | Biodiversity loss from entrainment, impingement, and brine discharge | 0.45 | 0.30 | 0.30 | 0.37 | 0.34 | 0.25 |
| | Habitat destruction due to high salinity, temperature, and chemicals. | 0.11 | 0.20 | 0.20 | 0.36 | 0.22 | 0.37 |
| | Disruption of marine food chains affecting fisheries and marine ecosystems | 0.06 | 0.10 | 0.05 | 0.11 | 0.11 | 0.16 |
| | Seabed pollution and increased bioaccumulation risks | 0.14 | 0.20 | 0.20 | 0.06 | 0.21 | 0.13 |
| | Seagrass loss impacts carbon sequestration and marine habitats | 0.24 | 0.20 | 0.25 | 0.11 | 0.12 | 0.09 |
| Groundwater Risks | Brine seepage contaminates groundwater with high salinity and chemicals. | 0.24 | 0.33 | 0.43 | 0.75 | 0.45 | 0.60 |
| | Over-extraction lowers water tables, reducing freshwater availability. | 0.66 | 0.53 | 0.13 | 0.13 | 0.15 | 0.13 |
| | Soil degradation from increased salinity, harming agriculture. | 0.11 | 0.13 | 0.44 | 0.13 | 0.4 | 0.27 |
| Water and Air Pollution | Increased turbidity and sediment suspension reduce water quality. | 0.30 | 0.17 | 0.17 | 0.29 | 0.2 | 0.62 |
| | Waste biomass from intake screens pollutes marine waters. | 0.46 | 0.17 | 0.17 | 0.24 | 0.2 | 0.08 |
| | Air pollution from desalination emissions. | 0.23 | 0.67 | 0.67 | 0.47 | 0.6 | 0.31 |
| Energy and Climate Risks | High energy demand increases carbon footprint. | 0.29 | 0.33 | 0.38 | 0.37 | 0.41 | 0.40 |
| | GHG emissions accelerate climate change. | 0.27 | 0.19 | 0.14 | 0.31 | 0.25 | 0.20 |
| | Waste heat discharge affects coastal environments. | 0.21 | 0.19 | 0.19 | 0.11 | 0.15 | 0.10 |
| | Rising operational expenditures (OPEX) due to energy-intensive operations & carbon taxes | 0.24 | 0.29 | 0.29 | 0.21 | 0.19 | 0.30 |
| Health Risks | Bioaccumulation of heavy metals in seafood. | 0.33 | 0.33 | 0.23 | 0.23 | 0.3 | 0.10 |
| | Air pollution exposure affects respiratory health. | 0.24 | 0.33 | 0.33 | 0.62 | 0.6 | 0.10 |
| | Chemical residues in desalinated water raise long-term health concerns. | 0.43 | 0.33 | 0.43 | 0.15 | 0.1 | 0.80 |
| Social and Economic Risks | Noise pollution affecting nearby communities. | 0.02 | 0.15 | 0.05 | 0.08 | 0.03 | 0.05 |
| | High Capital Expenditures (CAPEX) for plant construction and infrastructure. | 0.56 | 0.25 | 0.45 | 0.38 | 0.45 | 0.42 |
| | Coastal tourism declines due to environmental degradation. | 0.02 | 0.11 | 0.09 | 0.06 | 0.03 | 0.05 |
| | Fisheries loss from reduced fish populations, causing unemployment and need for social subsidies. | 0.02 | 0.03 | 0.03 | 0.02 | 0.12 | 0.05 |
| | Need for substantial subsidies or tariffs to keep desalinated water affordable. | 0.39 | 0.37 | 0.37 | 0.46 | 0.36 | 0.42 |

**TABLE 4**

**Normality and CSD test**

*Note: "***", '**', '*' refer to the significance level at 1, 5 and 10%. (.) refers to probabilities.*

## STRENGTHENING THE SUSTAINABILITY AND RESILIENCE OF THE DESALINATION SECTOR IN THE MEDITERRANEAN – FIRAS MARSIT

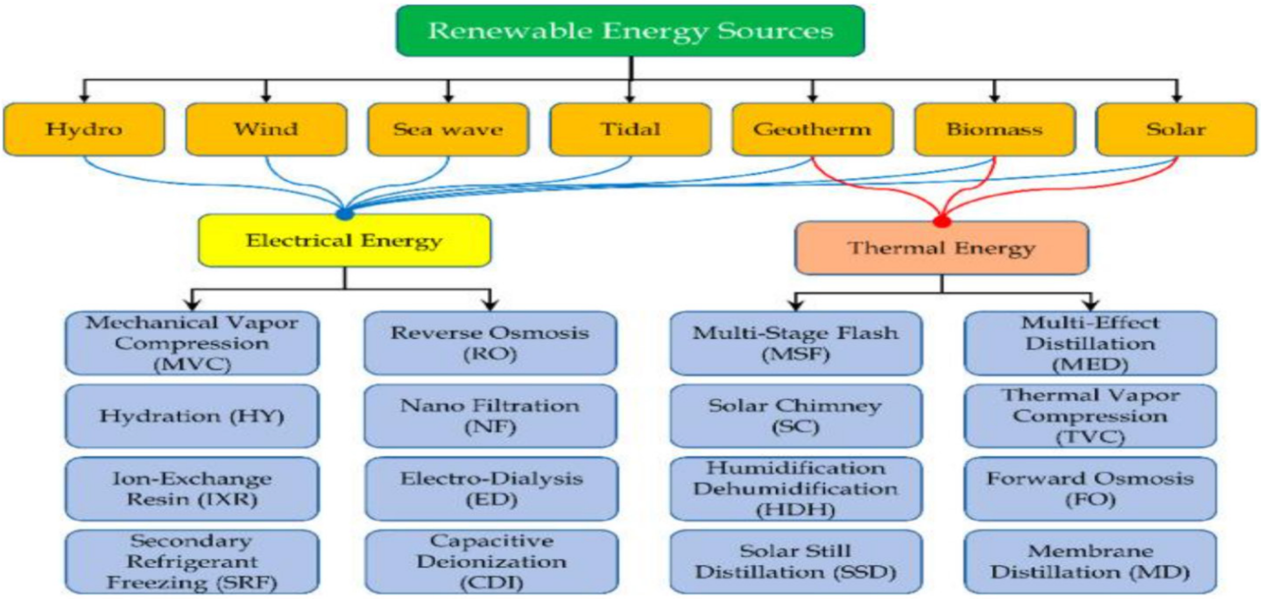


**Figure.1** *compatibility of desalination methods with renewable energy sources. Source:* https://www.mdpi.com/2076-3417/11/2/670

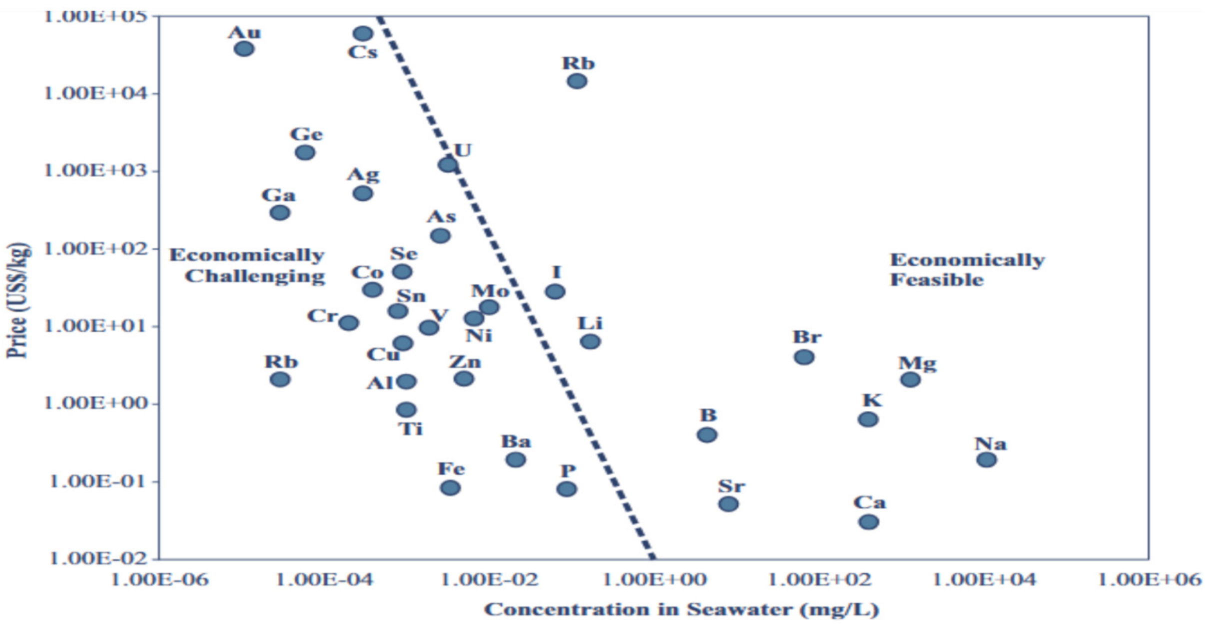


**Figure.2** *Economic feasibility to extract Boron, Lithium and other minerals from seawater. Source:* https://jbth.com.br/index.php/JBTH/article/view/418/354

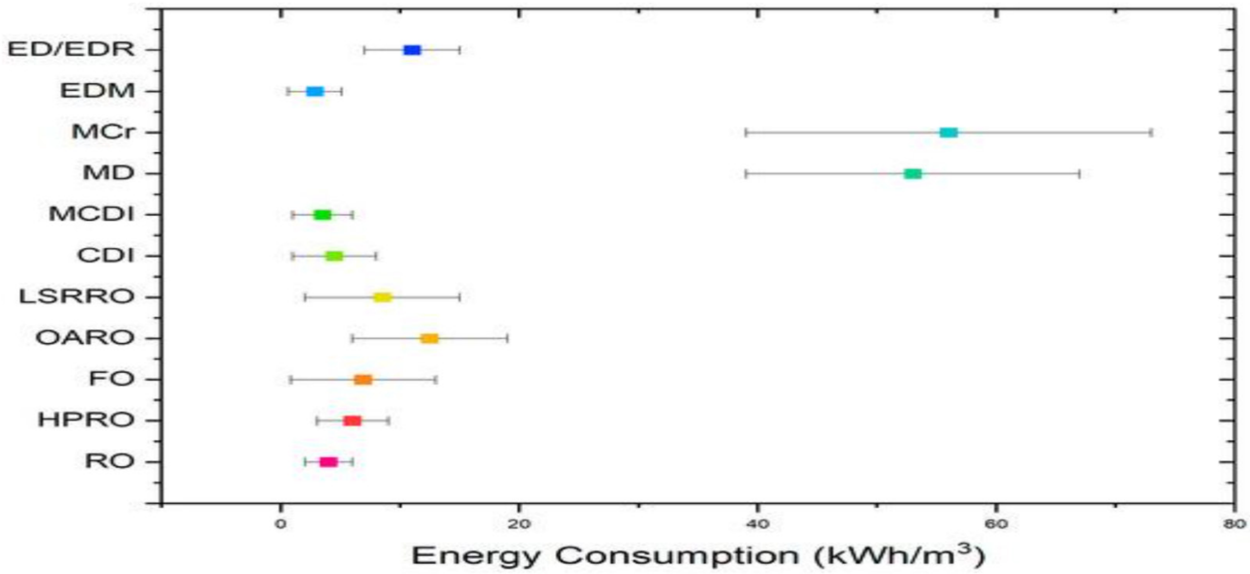


**Figure.3** *Energy consumption assessment of membrane-based desalination technologies. Source:* https://www.mdpi.com/1996-1073/18/4/962

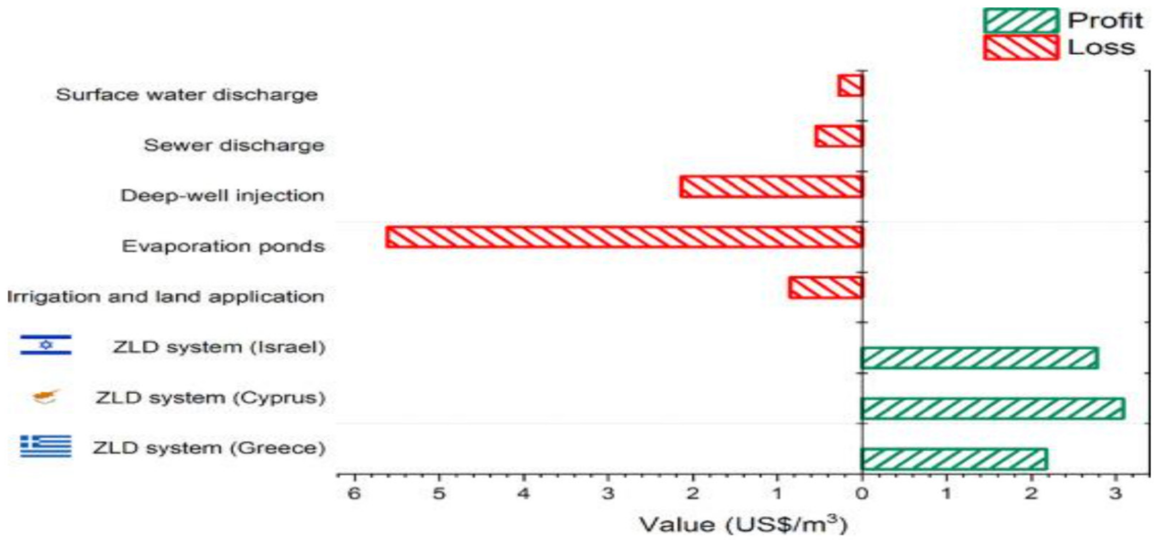


**Figure.4** *Benefits of ZLD system in Eastern Med countries. Source:* https://www.sciencedirect.com/science/article/pii/S0255270122002409

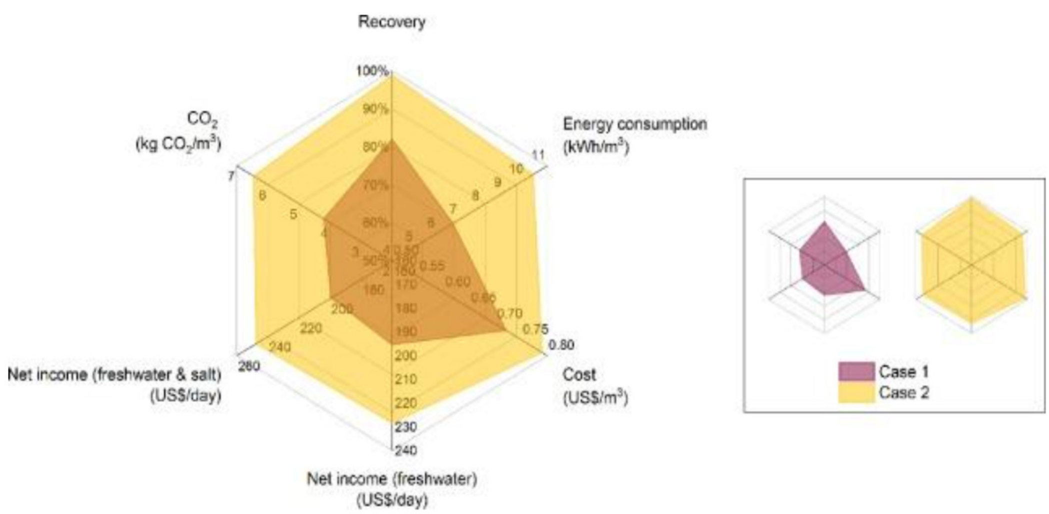


**Figure.5** *Overall Performance of MLD (Case 1) compared to ZLD (Case 2). Source:* https://www.sciencedirect.com/science/article/pii/S221313882200529X

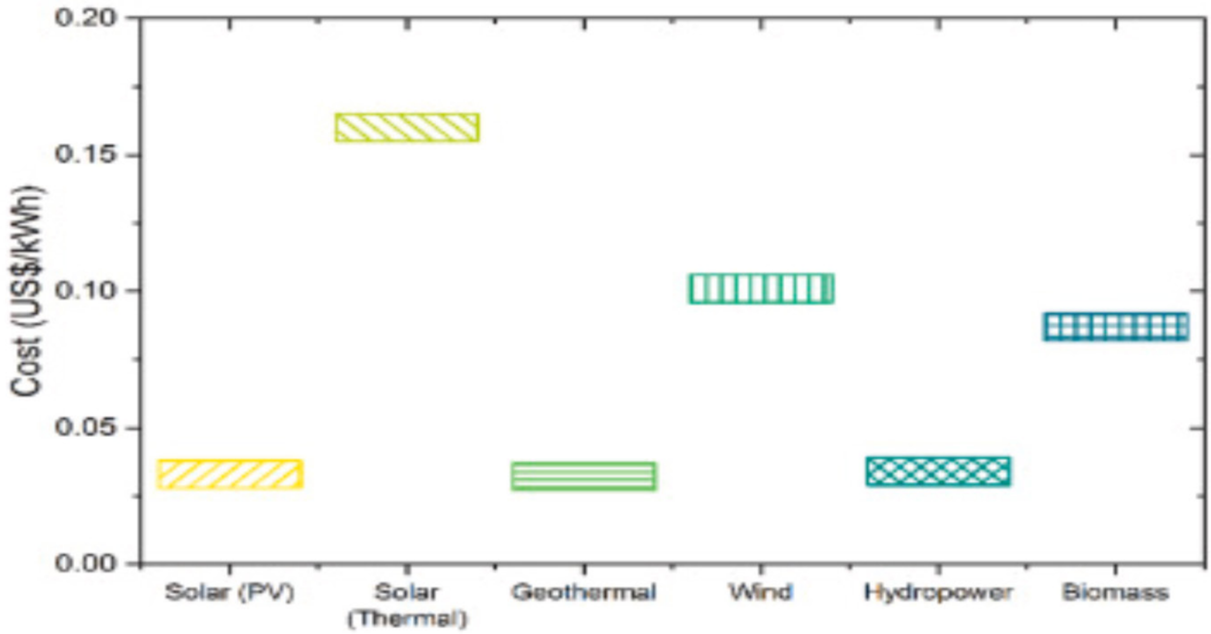


**Figure.6** *cost of electricity generated by renewable energy sources. Source:* https://www.sciencedirect.com/science/article/pii/S0301479722018126#fig2

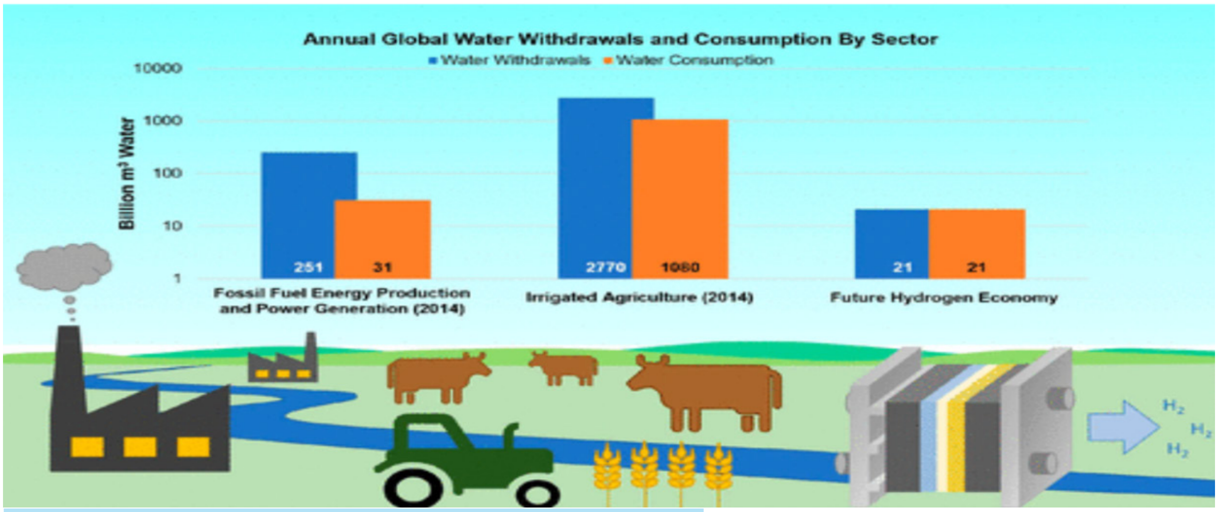


**Figure.7** *Comparison of the global freshwater withdrawal and consumption of different sectors. Source: ACS Energy Lett. 2021, 6, 9, 3167-3169*

# CAN DESALINATED WATER DRIVE AGRICULTURAL GROWTH IN ALGERIA? A FEASIBILITY STUDY FOR ECONOMIC AND SUSTAINABLE DEVELOPMENT – HADJER BOULILA, SEYF EDDINE BENBEKHTI, SALAH EDDINE SARI HASSOUN

| | | Activities | | | | Commodities | | | | Factors | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AGR | MAN | CON | SEV | AGR | MAN | CON | SEV | LAB | CAP | HH | GOV | INV | ROW |
| Activities | AGR | | | | | X | | | | | | | | | X |
| | MAN | | | | | | X | | | | | | | | X |
| | CON | | | | | | | X | | | | | | | X |
| | SEV | | | | | | | | X | | | | | | X |
| Commodities | AGR | X | X | X | X | | | | | | | X | X | X | X |
| | MAN | X | X | X | X | | | | | | | X | X | X | X |
| | CON | X | X | X | X | | | | | | | X | X | X | X |
| | SEV | X | X | X | X | | | | | | | X | X | X | X |
| Factors | LAB | X | X | X | X | | | | | | | | | | |
| | CAP | X | X | X | X | | | | | | | | | | |
| | HH | | | | | | | | | X | X | | | | |
| | GOV | X | X | X | X | | | | | | | | | | |
| | INV | | | | | | | | | | | X | X | | X |
| | ROW | X | X | X | X | X | X | X | X | | | | | | |
| ENV | BRINE | | X | | | | | | | | | | | | |
| | CO2 | X | X | X | X | | | | | | | | | | |

**Figure.A1** *Symbolic Structure of the Environmentally Extended Social Accounting Matrix (EE-SAM) for Algeria, 2023*
*Source: by the authors*

This symbolic SAM matrix illustrates the monetary and environmental interactions between production activities, commodities, factors, institutions, and the environment in the Algerian economy. An «X» marks the presence of a direct flow or transaction between accounts. The matrix integrates environmental extensions for $CO_2$ emissions and brine discharge from desalination and manufacturing. This theoretical version excludes numeric values to preserve confidentiality and support future model reuse.

| Abbreviation | Description |
|---|---|
| **AGR** | Agriculture |
| **MAN** | Manufacturing (includes Desalination) |
| **CON** | Construction |
| **SEV** | Services |
| **LAB** | Labor |
| **CAP** | Capital |
| **HH** | Households |
| **GOV** | Government |
| **INV** | Investment / Savings |
| **ROW** | Rest of the World (Imports/Exports) |
| **$CO_2$** | Carbon Dioxide Emissions |
| **BRINE** | Brine Discharge from Desalination |

**TABLE A2**
**Abbreviation Key for the EE-SAM matrix**
*Source : by the authors*

| Symbol | Parameter / Elasticity | Description | Value | Source / Assumption |
|---|---|---|---|---|
| **w_L** | Real wage rate | Real labor income (in million DZD per worker) | 0.125 | Calibrated from labor compensation / employment (EE-SAM) |
| **r_K** | Return to capital | Rental rate of capital per unit of capital stock | 0.180 | Calibrated from Capital income share from EE-SAM |
| **γ_i** | Emission coefficient ($CO_2$) | $CO_2$ tons per million DZD of output (manufacturing, desalination) | 0.35 for the baseline SAM and varies by scenario | IEA (2023); Abdelbaki et al. (2024) |
| **ß_brine** | Brine discharge ratio | Volume of brine per unit of desalinated water ($m^3$/$m^3$) | 1.1 for the baseline SAM and varies by scenario | Calculated based on Plan Bleu observatory; Martín-Gorriz et al. (2020) |
| **ε_energy** | Energy use per $m^3$ | kWh per cubic meter of desalinated water | 3.8 for the baseline SAM and varies by scenario | IEA (2023); Martín-Gorriz et al. (2020) |
| **λ_ag** | Labor intensity (agriculture) | Jobs per million DZD of agricultural output | 4.75 for the baseline SAM and varies by scenario | Calibrated Employment / output ratio in agricultural sector (EE-SAM) |
| **σ_c** | Elasticity of substitution in consumption | Substitution between commodities in CES utility function | 0.80 | Lofgren et al. (2002); Devarajan & Go (2003) |
| **σ_p** | Elasticity of substitution between factors | CES substitution between capital and labor in production | 0.60 | GTAP (2020); standard CGE calibration for developing economies |
| **n_d** | Price elasticity of water demand | Elasticity of demand for water in agriculture | −0.40 | Calzadilla et al. (2011); Roe et al. (2005) |
| **μ** | Armington elasticity | Elasticity between domestic and imported goods | 1.20 | GTAP database; standard in CGE models |
| **ρ** | CET export transformation elasticity | Elasticity of transformation between domestic supply and exports | 1.50 | FAO (2022); GTAP (2020); useful for CET functions in agriculture and manufacturing |

**TABLE A3**
**Model's elasticities and parameters**

| Model Feature | Closure Assumption |
|---|---|
| **Macro Closure** | Investment-driven model (savings adjust to investment) |
| **Government Balance** | Fixed government savings, flexible indirect tax rate |
| **External Balance** | Real exchange rate adjusts to maintain fixed trade balance |
| **Labor Market** | Labor fully employed, flexible real wage |
| **Capital Market** | Sector-specific capital (short run); mobile in long run |
| **Production Technology** | Constant returns to scale; nested CES/CET functions |
| **Price Numéraire** | Consumer price index (CPI) fixed at 1 |

**TABLE A4**
**Model's closure rules**

# GOVERNANCE AND EXECUTIVE REGULATORY TOOLS FOR A MORE SUSTAINABLE DESALINATION INDUSTRY IN ALGERIA – NAJET AROUA

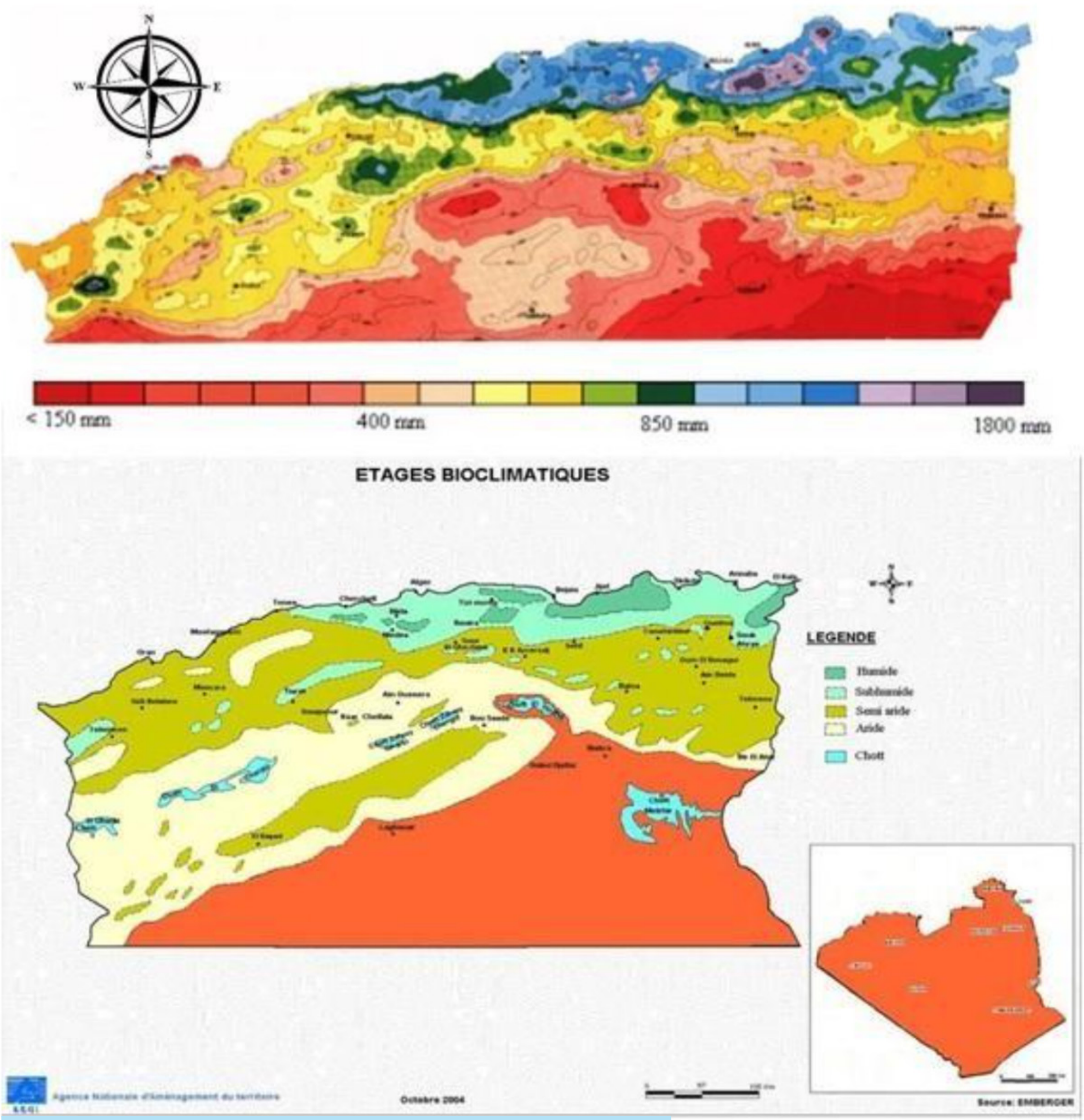


**Figure.1** *Precipitation and natural zones (ANRH, 2015 and ANAT, 2004)*

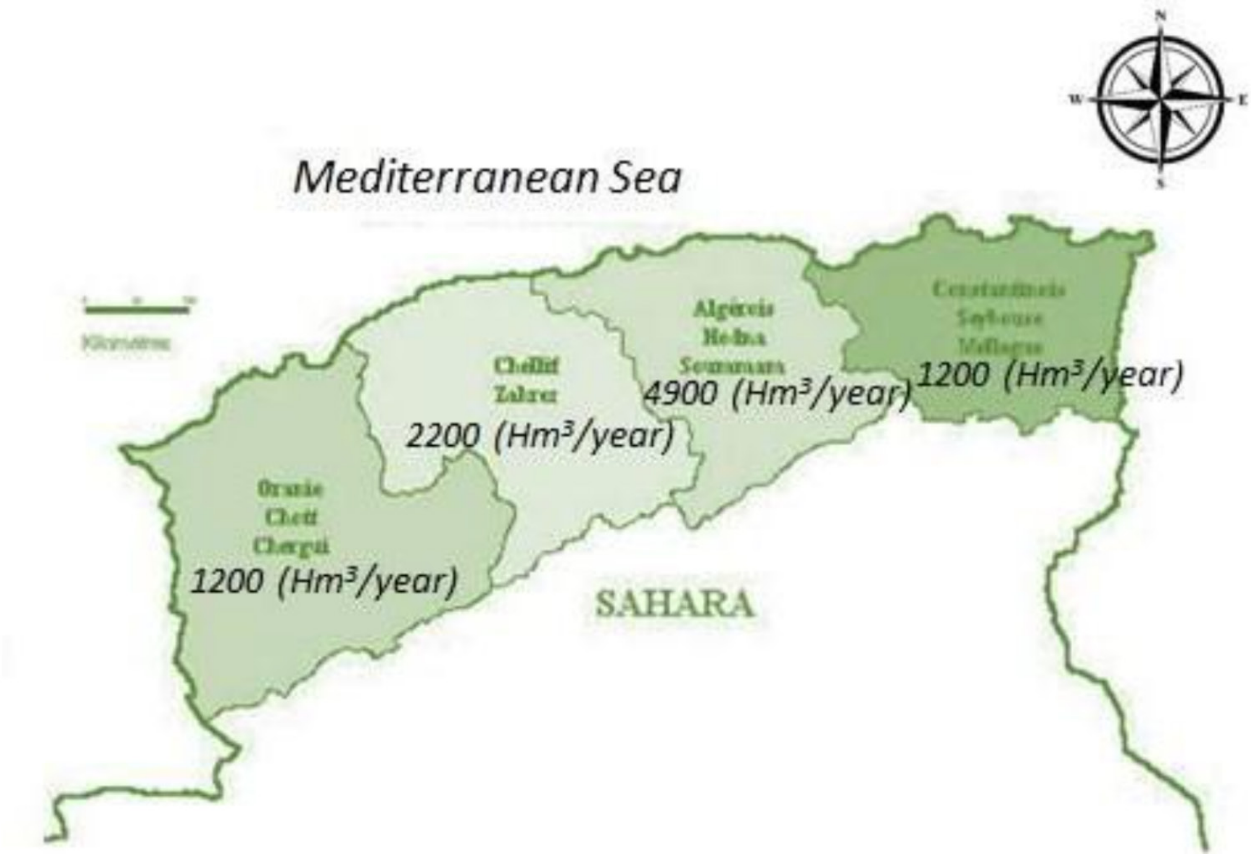


**Figure.2** *Hydrographic Basins in Algeria (ANRH,2004)*

| Northern hydrographic region | Wilaya | Nb of coastal municipalities/ total nb of municipalities | Coastal municipalities supplied with desalinated water | Nb of SDWP |
|---|---|---|---|---|
| **Oranie-Chott Chergui** | **Tlemcen** | **08/53** | **04** | **05** |
| | Ain Temouchent | | - | 02 |
| | **Oran** | **14/26** | **03** | **09** |
| | Mostaganem | | 01 | 01 |
| | | | **Sub-total** | 17 |
| **Chelif-Zahrez** | Relizane | | - | 00 |
| | Chlef | | 01 | 01 |
| | Aïn Defla | | - | - |
| | Tissemsilt | | - | - |
| | Médéa | | - | - |
| | | | **Sub-total** | 01 |
| **Algérois-Hodna-Soumam** | Tipaza | | | 04 |
| | **Algiers** | **18/57** | | **12** |
| | Boumerdes | | | 03 |
| | Tizi-Ouzou | | | 02 |
| | Bejaia | | | 01 |
| | | | **Sub-total** | 23 |
| **Jijel Skikda Annaba El-Tarf** | Jijel | | - | |
| | **Skikda** | **14/38** | **01** | **07** |
| | Annaba | | - | |
| | El-Tarf | | - | |
| | | | **Sub-total** | **07** |
| | | | **Total** | **48** |

**TABLE 1**
**Deployment of SWDPs along the coastal zone in Algeria (according to the Ministry of Water Resources and Water Security, and Plan Bleu, 2025).**

| TDS (mg/L) | Water Quality | Typical Uses |
|---|---|---|
| < 300 | Excellent | Drinking water (ideal), pharmaceutical use, sensitive industrial processes |
| 300–600 | Good | Drinking water (acceptable), food processing, domestic use |
| 600–1000 | Fair | Acceptable for drinking (taste may be affected), general irrigation |
| 1000–2000 | Poor | May be used for irrigation (with monitoring), livestock watering |
| 2000–5000 | Very poor | Limited agricultural use (salt-tolerant crops), some industrial applications |
| > 5000 | Not recommended for human use | Industrial processes only, requires treatment before other uses |

**TABLE 2**
**Total Dissolved Solids (TDS) range and water quality (WHO, 2022, Guidelines for Drinking-water Quality)**

| Location Wilaya) | Nb of coastal /total nb of municipalities | Municipalities supplied | Population (estimated in 2020) | Surface (Km2) | Nb of SWDP (drinking water) | SWDP (industrial water) |
|---|---|---|---|---|---|---|
| **TLEMCEN** | 08/53 | Honaine | 6 872 | 137 | 1 | - |
| | | Ghazaouet | 42 911 | 177 | 2 | - |
| | | Souk Thlata | 3 516 | 85 | 1 | - |
| **ORAN** | 14/26 | Arzew | 108 319 | 71,90 | 3 | 4 |
| | | Bethioua | 22 226 | 108,57 | 1 | - |
| | | Oran | 721 825 | 64,00 | - | 1 |
| **ALGIERS** | 18/57 | Ain Benian | 75 739 | 16,00 | 3 | - |
| | | Hammamet | 26 582 | 8,54 | 2 | - |
| | | Reghaïa | 94 685 | 27,25 | 1 | - |
| | | Bordj el-Kifan | 168 367 | 21,7 | 4 | - |
| | | Staouali | 52 814 | 22,00 | 2 | - |
| | | Hamma Anasser | 75 206 | 2,18 | 1 | - |
| **SKIKDA** | 14/38 | Skikda | 202 567 | 52,00 | 4 | 2 |

**TABLE 3**
**Existing seawater desalination plants in the four wilayate case studies (Plan Bleu, MRESH and ANIREF, 2025)**

| Data Category | Purpose of Use | Analysis method | Expected Outcome |
|---|---|---|---|
| **Geo-location** | Location (wilaya+municipality) Distance to the sea Distance to the supplied area | Geospatial Analysis and Distance Calculation | nland/offshore plants/distance to high-quality seawater<br>Coastal ecosystems at risk<br>Water use (domestic, tourism, industry) Nearby fragile ecosystems/protected areas<br>Population and local water needs (various purpose)<br>Daily per capita water requirement and allocation» Estimated transport distance and cost<br>Site selection criteria<br>Possibility to supply with locally available renewable energy (electricity, sun, wind)<br>Operating natural conditions (climate, marine currents, temperature, etc)<br>Nearby waste treatment plants<br>Nearby economic infrastructure ( petroleum terminal, port, logistic network) |
| **Production capacity** | Specific data | Calculation | % needs covered<br>Contribution to the improvement of the water security index |
| **Size + nb of units** | Surface area Associated treatment, distribution, and storage infrastructure | Comparison with standards | Modularity and flexibility of the SWDP Energy performance and optimization |
| **Online date** | Operating duration and end date | Calculation | Estimated lifespan (20 to 25 years) |
| **Employed technology** | Operating process Energy used (type and volume) | Comparison with standards and data collected | Water quality / typical use<br>Environmental impact –risk management Discharges (type and volume) |
| **Primary water supply source** | Surface/groundwate r Conventional/non-c onventional resources | | Estimated water demand satisfaction rate |

**TABLE 4**
**Application of Collected Data[10]**

| Population | l/unhab/day |
|---|---|
| < 10 000 unhab | 85 |
| 10 000 – 20 000 | 100 |
| 20 000 – 50 000 | 160 |
| 50 000 – 100 000 | 180 |

**TABLE 5**
**Per capita drinking water allocation (according to the Ministry of Water Resources, 2004)**

| Designation | Specific purpose |
|---|---|
| Executive Decree N°07-206 of 30 June 2007 setting the conditions and procedures for construction and land use along the coastal strip, the occupation of natural areas adjacent to beaches, and the extension of non-aedificandi zones | Activities are only allowed in a coastal strip extending 3 kilometres inland from the shoreline. No activity is allowed in a coastal strip extending 300 metres inland from the shoreline, except of seaside touristic activities (Art. 9). |
| Executive Decree N° 06-351 of 5 October 2006 setting the conditions for the construction of new carriage roads running parallel to the shoreline. | Any new paved road parallel to the sea should be previously included into the master urban plan accompanied with an environmental impact assessment study and must be maximum 08 meters wide (Art. 3). |
| Executive Decree N° 09-88 of 17 February 2009 related to the designation of critical coastal zones | The designation of critical coastal zones results from a specific study of the local geomorphology and environmental characteristics (Art. 2). This study includes the delineation of the coastal study area, its general physical characteristics (pedology, geomorphology), the dominant wave patterns, shoreline dynamics, pressures and causes of degradation, vulnerability assessment, recommended protection measures, and proposed zoning (Art. 3). |

**TABLE 6**
**Selected executive decrees governing the coastal zone management.**

| Wilaya | Municipality | Project name | Capacity (m³/d) | Size | Online date | *Nominal expected operational lifespan** |
|---|---|---|---|---|---|---|
| **Tlemcen** | Honaine | Tlemcen-Honaine | 200 000 | XL | 2012 | 2037 |
| | Ghazaouet | Ghazaouet 1 | 2500 | M | 2003 | 2029 |
| | Ghazaouet | Ghazaouet 2 | 2500 | M | 2004 | 2029 |
| | Souk Thlata | Souk Tleta | 199848 | XL | 2010 | 2035 |

**TABLE 7**
**Seawater Desalination Plants in Coastal Municipalities-Wilaya of Tlemcen: Key Parameters**

| Wilaya | Municipality | Project name | Main customers | Capacity (m³/d) | Size | Online date | *Nominal expected operational lifespan** |
|---|---|---|---|---|---|---|---|
| **Oran** | Arzew | Arzew IWPP | Municipalities as drinking water (TDS 10ppm - <1000ppm) | 88888 | XL | 2006 | 2031 |
| | Arzew | Arzew | Id. | 50 | S | 2010 | 2035 |
| | Arzew | Arzew | Id. | 1920 | M | 2002 | 2027 |
| | Bethioua | Bethioua | Id. | 5000 | M | 2003 | 2028 |

**TABLE 8**
**Seawater Desalination Plants in Coastal Municipalities-Wilaya of Oran: Key Parameters**

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