الجمهورية الجزائرية الديمقراطية الشعبية
People's Democratic Republic of Algeria
وزارة التعليم العالي والبحث العلمي
Ministry of Higher Education and Scientific Research
جامعة عين تموشنت بلحاج بوشعيب
University of Ain-Temouchent- Belhadj Bouchaib
. Faculty of Science and Technology

Master's degree thesis
Sector : HYDRAULICS
Specialty : URBAN HYDRAULICS

Topic :

Multi-Criteria Analysis of Seawater Desalination Plants in Algeria: Development of a Spatial Database and Performance Evaluation Software

presented by:

ZAIMI NADIR

Sustained on 29/06/2025

JURY COMPOSED OF:

PRESIDENT : Mme BENCHEKOR HASSIBA

EXAMINER : MR KADDOUR HAKIM

SUPERVISOR : MR NEHARI ABDE ARRAHMANE AND MOSTEFAOUI LEILA

SESSION YEAR 2024/2025

ACKNOWLEDGMENTS

First and foremost, I extend my deepest gratitude to God, the Almighty and Most Merciful, for granting me the strength, patience, and perseverance to carry out and complete this humble work.

I would like to thank my supervisor, Mr. Nehari Abderrahmane, for his continuous support and constructive advice throughout this research.

I would like to express my sincere gratitude and profound appreciation to Professor Kaddour Hakim and Dr. Leïla Mostefaoui for their invaluable guidance, constructive criticism, and unwavering support throughout this project. Their academic mentorship and inspiring presence greatly enriched the quality of this research, providing me with continuous encouragement and motivation.

I am also grateful to the esteemed members of the jury for taking the time to examine my work. Their valuable observations and feedback will undoubtedly contribute to enriching my understanding of the subject.

I would like to express my sincere gratitude to Mr. Bouzada Cheikh, Mr. Mahmoud Makhloufi, and Mr. Belaidi Atallah, engineers at BWC, for their generous support and the valuable guidance they provided throughout my internship. Their professional insights and encouragement greatly contributed to the success of this experience.

My heartfelt thanks go to all my professors, whose knowledge, mentorship, and patience have played a fundamental role in shaping my academic and personal growth over the years.

Lastly, I would like to thank everyone who, in one way or another, contributed to the completion of this work.

NADIR ZAIMI

Dedication

Praise be to Allah, who taught mankind what he did not know, who granted him the gift of reason to guide his path in the pursuit of knowledge and understanding. Praise be to Him for every moment in which He facilitated success, both in the visible and the unseen.

To my dear family, the first to believe in me unconditionally and to support me without hesitation,

To my beloved parents, the source of my life and the light of my path, whose prayers and encouragement have been my strength. You planted in me the love of knowledge and the value of hard work — you were the beginning of the journey and the essence of this achievement.

To my siblings and extended family, who were my warmth in difficult times, my support in moments of hardship, and my joy in every step forward.

To my friend Nadir, whose sincere support, valuable assistance, and constant presence left an unforgettable mark on this research.

And to my dear friends, who shared the path with love and honesty, who brought comfort in moments of exhaustion, stood by me in times of doubt, and whose laughter brightened even the hardest of days.

To all those who extended a helping hand — even with just a word or a piece of advice — and to my professors and all the devoted scholars who dedicated their lives to the pursuit of knowledge: you have my deepest respect and gratitude.

NADIR ZAIMI

Abstract

This study aims to develop a comprehensive database containing all the technical and spatial information related to seawater desalination plants in Algeria, using Geographic Information Systems (GIS). The work focuses on collecting and organizing available data regarding the location of these plants, their production capacity, and the type of technology used, within an accurate spatial database framework. The Global Mapper software was used to input and analyze the data and to create thematic maps that illustrate the geographic distribution of the plants along the Algerian coastal strip.

Additionally, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) will be employed to rank the desalination plants based on their performance, using a set of technical, environmental, and social criteria. This contributes to informed decision-making and the determination of intervention priorities.

This study offers a practical tool to support relevant stakeholders in planning and monitoring desalination projects, highlighting the critical role of these plants in enhancing national water security amid climate change and increasing pressure on traditional water resources.

Keywords: geographic information systems, Desalination, Global Mapper, Technique for Order Preference by Similarity to Ideal Solution

Résumé

Cette étude vise à développer une base de données complète contenant toutes les informations techniques et spatiales relatives aux stations de dessalement d'eau de mer en Algérie, en utilisant les Systèmes d'Information Géographique (SIG). Ce travail se concentre sur la collecte et l'organisation des données disponibles concernant la localisation de ces stations, leur capacité de production et la technologie utilisée, dans le cadre d'une base de données spatiale précise. Le logiciel Global Mapper a été utilisé pour la saisie et l'analyse de ces données, ainsi que pour la création de cartes thématiques illustrant la répartition géographique des stations le long de la bande côtière algérienne.

Par ailleurs, la méthode d'analyse multicritère TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) sera utilisée pour classer les stations de dessalement selon leurs performances, en se basant sur un ensemble de critères techniques, environnementaux et sociaux. Cela contribue à appuyer la prise de décision et à définir les priorités d'intervention.

Cette étude offre ainsi un outil pratique au service des acteurs concernés pour la planification et le suivi des projets de dessalement, tout en mettant en lumière le rôle stratégique de ces infrastructures dans le renforcement de la sécurité hydrique nationale face aux changements climatiques et à la pression croissante sur les ressources en eau conventionnelles.

Mots-clés : Système d'Information Géographique (SIG), Dessalement, Global Mapper, Technique de Préférence par Similarité à la Solution Idéale (TOPSIS)

الملخص

تهدف هذه الدراسة إلى إنشاء قاعدة بيانات شاملة تحتوي على جميع المعلومات التقنية والمجالية المتعلقة بمحطات تحلية مياه البحر في الجزائر، وذلك باستخدام نظم المعلومات الجغرافية .(GIS) يركّز هذا العمل على تجميع وتنظيم المعطيات المتوفرة حول مواقع هذه المحطات، سعتها الإنتاجية، ونوع التكنولوجيا المستخدمة، في إطار قاعدة بيانات مكانية دقيقة. تم استخدام برنامج Global Mapper في إدخال وتحليل هذه البيانات وإنشاء خرائط موضوعية توضّح التوزيع الجغرافي للمحطات على طول الشريط الساحلي الجزائري.

كما سيتم استخدام أسلوب تحليل المفاضلة متعددة المعايير (TOPSIS) لترتيب محطات التحلية حسب أدائها، استناداً إلى مجموعة من المعايير التقنية والبيئية والاجتماعية، مما يساهم في دعم اتخاذ القرار وتحديد أولويات التدخل.

تساهم هذه الدراسة في توفير أداة عملية لدعم الجهات المعنية في التخطيط ومتابعة مشاريع التحلية، كما تبرز الدور المحوري لهذه المحطات في تعزيز الأمن المائي الوطني في ظل التغيرات المناخية والضغط المتزايد على الموارد التقليدية.

الكلمات المفتاحية: تحلية المياه، تقنية التفضيل حسب التشابه مع الحل المثالي، نظام المعلومات الجغرافية

Contents

Abbreviations

Abbreviation	**Full Form**
AHP	Analytic Hierarchy Process
BWC	Beni Saf water company
DZD	Algerian Dinar
ED	Electrodialysis
EDR	Electrodialysis Reversal
GIS	Geographic Information System
KML	Keyhole Markup Language
kWh	kilowatt-hour
MCDM	Multi-Criteria Decision Making
MED	Multi-Effect Distillation
MSF	Multi-Stage Flash (distillation)
m^3/day	cubic meters per day
RO	Reverse Osmosis
SIG	Geographic Information System (French equivalent of GIS)
SWRO	Seawater Reverse Osmosis
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VCD	Vapor Compression Distillation
ZLD	Zero Liquid Discharge

Figures list

Tables List

General Introduction

"Water is the source of all life, yet it is becoming increasingly scarce." What was once considered a distant concern has now become a pressing global issue. Climate change, rapid population growth, urban expansion, and the overexploitation of freshwater resources are exacerbating water stress, especially in arid and semi-arid regions such as Algeria. Confronted with these challenges, countries are compelled to adopt sustainable solutions to ensure access to safe drinking water. Among these solutions, seawater desalination has emerged as an essential alternative.

Since the early 2000s, Algeria has adopted an ambitious policy to develop seawater desalination infrastructure, aiming to meet growing water demands, particularly in densely populated coastal areas. As a result, several desalination plants have been commissioned along the Algerian coast. However, for these facilities to effectively contribute to national water security, it is crucial to have modern tools capable of efficiently collecting, organizing, and analyzing both technical and spatial data related to their operation.

As Algeria faces increasing water scarcity due to climate change, population growth, and urbanization, the reliance on seawater desalination as a sustainable solution presents a dual challenge: how to effectively manage the operational and strategic planning of desalination plants while ensuring that decision-making processes are data-driven and reflective of local needs. This raises several key questions:

1. How can Geographic Information Systems (GIS) be utilized to efficiently collect and analyze data related to the operation of desalination plants in Algeria?
2. In what ways can multi-criteria decision-making tools, such as the TOPSIS method, enhance the planning and evaluation of these plants in terms of performance, sustainability, and resource allocation?

In this context, Geographic Information Systems (GIS) represent a robust technological solution. By combining spatial and attribute data, GIS enables the visualization, integration, and management of complex information, which is essential for informed planning and decision-making in water infrastructure projects. Furthermore, the need for evaluating and prioritizing interventions highlights the importance of decision-support tools based on multi-criteria analysis.

This thesis falls within this perspective. Its main goal is to develop a comprehensive GIS-based spatial database of seawater desalination plants in Algeria, utilizing the capabilities of Global Mapper, a software widely recognized for its advanced spatial data processing features. More importantly, the thesis focuses on the development of a software program that integrates the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)—a widely used multi-criteria decision-making method. It is important to clarify that the objective is not to evaluate the current performance of desalination plants, but rather to design a flexible, user-oriented tool that will enable future performance evaluations based on customizable criteria and weights.

The TOPSIS method, known for its simplicity and reliability, will be embedded within a user-friendly application designed to interact with spatial and technical data. This combination of spatial analysis and decision-support features aims to provide engineers, planners, and policymakers with a practical tool to enhance the management and planning of desalination projects across the country.

The methodology adopted in this work is structured around key steps: the collection and structuring of technical and spatial data related to desalination plants in Algeria; the integration of this data into a GIS environment using Global Mapper; and finally, the development of a graphical interface that allows users to interact with the data and apply the TOPSIS algorithm. The work combines both theoretical foundations and practical implementation, with an emphasis on accessibility and adaptability.

The thesis is organized as follows:

- **Chapter One: Literature Review on Desalination and the Regional Context**

  This chapter provides a general overview of desalination technologies, their development in the MENA region, and a specific examination of the current state of seawater desalination in Algeria. It also provides background on water stress and the strategic importance of desalination.

- **Chapter Two: State of the Art in Geographic Information Systems (GIS)**

  This chapter introduces the principles and capabilities of GIS, with a special focus on its application in managing and analyzing infrastructure data. The role of software like Global Mapper is emphasized in handling spatial data related to desalination plants.

- **Chapter Three: Compilation and Presentation of Empirical Data**

  This chapter details the process of data collection, geolocation using Google Earth, integration into Global Mapper, and the structuring of a spatial database. It describes the technical and spatial characteristics of existing desalination plants in Algeria.

- **Chapter Four: Exporting Data and Developing the TOPSIS Application**

  This chapter focuses on exporting the processed data and building the decision-support application using Python and Tkinter. It provides a step-by-step explanation of the TOPSIS method and discusses the design, logic, and functions of the developed GUI tool.

Through this work, we aim to contribute to the advancement of digital tools for water resource management in Algeria, offering a flexible and scalable decision-support application to promote sustainable and informed development of desalination projects.

Chapter One

Desalination Literature Review

1 Global Overview of Desalination Technology

Desalination technology has emerged as a strategic response to growing global water scarcity, driven by population growth, climate change, and increasing demand for freshwater in arid and semi-arid regions. The process involves removing salts and other impurities from seawater or brackish water to produce potable water suitable for human consumption, agriculture, or industrial use.

There are two main categories of desalination technologies: thermal processes and membrane-based processes.

Thermal desalination, such as Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED), involves heating seawater to produce vapor, which is then condensed into freshwater. These methods are energy-intensive and are commonly used in oil-rich countries in the Middle East, where energy is relatively inexpensive.

Membrane desalination, particularly Reverse Osmosis (RO), is currently the most widely used technology globally. It involves applying high pressure to force seawater through semi-permeable membranes that block salts and other contaminants. RO is more energy-efficient and has become increasingly cost-effective due to advancements in membrane materials and energy recovery systems.

As of 2024, more than 190 countries operate desalination plants, with a global production capacity exceeding 120 million cubic meters per day. Major contributors include Saudi Arabia, the United Arab Emirates, the United States, Spain, and China. In addition to large-scale centralized plants, small and mobile desalination units are increasingly deployed in remote or emergency contexts.

However, despite its benefits, desalination poses environmental and economic challenges. These include high energy consumption, brine disposal issues, and **cost** implications, especially for low-income countries. Innovations are underway to address these concerns, including the integration of renewable energy sources (solar, wind) and the development of low-pressure membranes and zero-liquid discharge (ZLD) technologies.

In conclusion, desalination is a rapidly evolving field that plays a vital role in achieving water security worldwide. Its continued development depends on enhancing efficiency, reducing environmental impacts, and making the technology accessible to a broader range of communities.

2 History and Development of Desalination Technologies

Desalination, the process of removing salts and other minerals from seawater, has evolved significantly over the past century. Early civilizations such as the Greeks and Romans used primitive distillation techniques, boiling seawater and collecting the steam to obtain fresh water. However, the modern era of desalination started in the mid-20th century, particularly in arid countries like Kuwait and Saudi Arabia. These countries began to explore thermal desalination technologies, such as Multi-Stage Flash (MSF), to meet their growing water demands. The 1970s energy crisis and the increasing need for freshwater further accelerated research and investment in this field

In the late 1980s and 1990s, membrane-based technologies, particularly Reverse Osmosis (RO), started gaining popularity. This shift was driven by technological advances in membrane materials and energy recovery systems, making RO more efficient and cost-effective. Today, desalination plays a vital role in global water supply strategies, especially in arid and semi-arid regions. It is used not only for municipal water supply but also for industrial and agricultural purposes. Continued innovations, cost reductions, and integration with renewable energy sources have contributed to the expansion of desalination across more than 150 countries worldwide (sciencedirect, 2025)

3 Types of Desalination Methods

Desalination technologies are generally classified into two main categories: thermal methods and membrane-based methods. Thermal desalination includes processes like Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED). In MSF, seawater is heated and then flashed into steam in multiple stages of decreasing pressure, with the steam then condensed into freshwater. MED, on the other hand, uses a series of vessels (effects) where steam from one effect is used to evaporate seawater in the next, resulting in higher efficiency (Darwish, 2005)

3.1 Thermal Desalination

Overview

Thermal desalination methods work by heating salty water to turn it into vapor, which is then cooled down and turned back into fresh water with low salt content. One big advantage of this method is that it doesn’t rely on how salty the original water is—it works just as well with very salty water. That’s why thermal desalination is commonly used in Middle Eastern countries like Saudi Arabia, Oman, Qatar, the UAE, Bahrain, and Kuwait. These countries use very salty sources like the Red Sea, the Persian Gulf, the Gulf of Oman, and the Indian Ocean. Today, about 75% of all thermal desalination plants in the world are found in the Arabian Peninsula, and half of those are in Saudi Arabia.

3.1.1 Multi-Stage Flash Distillation (MSF)

Multi-Stage Flash Distillation (MSF) is one of the most widely implemented thermal desalination techniques, particularly in regions characterized by abundant energy resources and high-water scarcity, such as the Middle East. The process relies on the principle of flashing—the rapid evaporation of water when it is exposed to a pressure lower than its saturation pressure at a given temperature.

In MSF systems, seawater is first heated to a high temperature, typically between 90°C and 120°C, in a heat exchanger. This heated brine then flows through a series of successive chambers or "stages", each maintained at progressively lower pressures. As the heated water enters each stage, the reduction in pressure causes a portion of it to instantaneously vaporize or "flash" into steam. The remaining brine continues to flow into the next stage, undergoing the same process. The vapor produced in each stage is then condensed on heat exchanger tubes that carry the incoming cold seawater, which in turn gets preheated before entering the brine heater. This configuration allows for effective heat recovery, enhancing the overall thermal efficiency of the system. (Shafique, 2019)

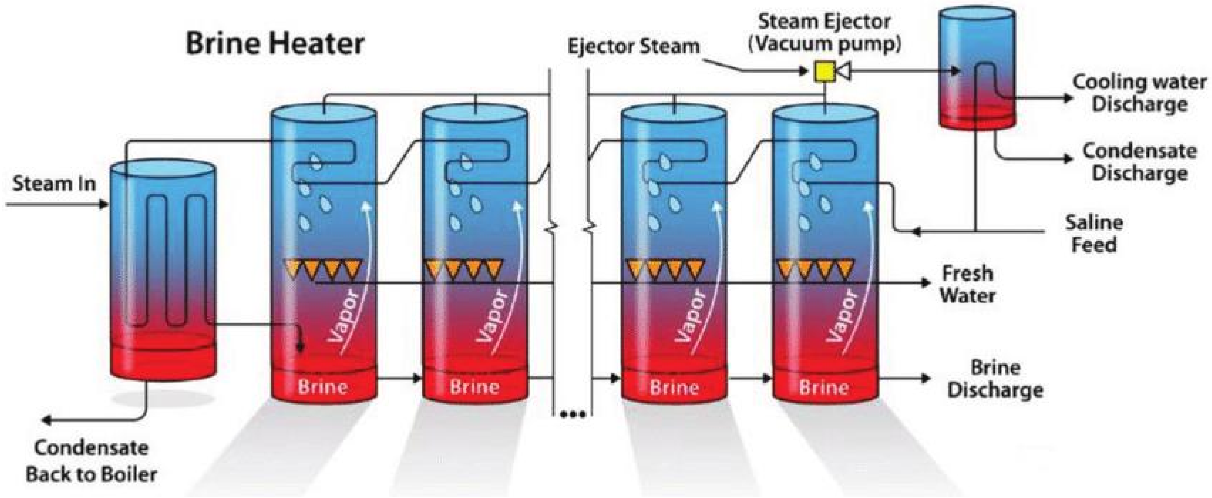


Figure 1:Diagram of a multistage flash distillation (MSF)

MSF units are typically constructed with 15 to 25 stages, and the efficiency of the process is commonly evaluated using the Gain Output Ratio (GOR), which represents the amount of distillate produced per unit of thermal energy input. A well-designed MSF plant may achieve a GOR ranging from 8 to 12, depending on the configuration and the quality of feedwater.

One of the major advantages of MSF lies in its robustness and its ability to handle feedwater with high salinity or contamination, which may pose challenges for membrane-based processes. Moreover, when integrated with power generation plants (a configuration known as co-generation), MSF can utilize low-cost or waste heat, thereby improving its economic viability.

However, the MSF process is also associated with high energy consumption, particularly in terms of thermal energy, and requires significant capital investment due to the need for corrosion-resistant materials and large infrastructure (Voutchkov, 2012 – Book). Despite these limitations, MSF remains a reliable choice for large-scale desalination in energy-rich regions.

A notable implementation of this technology is found in the Ras Al-Khair Desalination Plant in Saudi Arabia, which combines MSF with other processes and produces over 1 million cubic meters of potable water per day, serving as a critical component of the nation’s water infrastructure.

CATEGORY	DETAILS
ADVANTAGES OF MSF	• High reliability and durability • High purity of product water • Long operational lifespan (20–30 years) • Suitable for large-scale production • Effective waste heat utilization (cogeneration) • Resistant to salinity variations • Lower sensitivity to seawater fouling vs. membranes • Stable operation with fewer shutdowns • Mature and well-understood technology • Easy to automate and control

Figure 2: Ras Al-Khair Desalination Plant in Saudi Arabia (UTILITIES, 2025)

Tableau 1: MSF technology

DISADVANTAGES OF MSF	• High thermal energy consumption • High capital/maintenance costs • Large footprint • Scaling/corrosion issues in equipment • Chemical dosing required • High brine discharge impacts marine life • Complex mechanical design (multi-stage systems) • Long construction/commissioning time • Not economical for small/medium plants • Lower efficiency vs. modern RO systems
RECENT ADVANCEMENTS	• Hybrid systems: Integration with RO for higher efficiency • Advanced materials: Anti-corrosive alloys and coatings • Waste heat recovery: Improved cogeneration designs • AI/automation: Optimized stage temperature control • Brine management: Zero Liquid Discharge (ZLD) adaptations • Modular designs: Reduced footprint and faster deployment • Renewable energy: Solar-thermal MSF pilot projects • Nanotechnology: Scale-resistant surface treatments

3.1.1.1 Improved Heat Recovery Systems

New designs focus on enhancing the heat recovery process to minimize thermal losses. Advanced materials, such as titanium and special alloys, are now being used in heat exchangers, reducing scaling and corrosion. For Example, the Shoaiba Desalination Plant in Saudi Arabia upgraded its heat recovery loops, improving overall plant efficiency by about 8%.

3.1.1.2 Hybrid Systems Integration

MSF units are being increasingly combined with Reverse Osmosis (RO) systems to form hybrid plants, aiming for improved energy optimization.

The Jebel Ali plant in the UAE introduced an MSF-RO hybrid system, reducing its energy consumption by 20% compared to traditional MSF alone.

Modern MSF plants now incorporate thermodynamic optimization**,** utilizing new technologies such as energy recovery turbines and vacuum-enhanced flashing, which reduce specific energy consumption.

3.1.1.3 Improved Anti-Scaling and Pretreatment Techniques

New chemical pretreatment solutions and nanotechnology-based anti-scaling agents have significantly extended plant lifespan and reduced maintenance downtime. (Drioli E. , 2011) Barka MSF Plant in Oman reported a 30% decrease in scaling incidents after adopting nanotechnology pretreatment.

Figure 3 :Baraka MSF plant in Oman (barkadesalination, 2025)

3.1.1.4 Future Prospects of MSF Desalination

Integration with Renewable Energy Sources

In the future, MSF plants are expected to increasingly utilize solar thermal energy to meet their heating needs, thereby reducing their dependency on fossil fuels. (IRENA, 2025)

Example:

A pilot solar MSF project in Tunisia demonstrated a 60% reduction in CO_2 emissions compared to conventional MSF plants.

3.1.1.5 3.2 Development of Modular MSF Units

Research is focusing on developing modular MSF units that are small, scalable, and mobile. These systems can be rapidly deployed in disaster-stricken or remote areas.

Example:

In Qatar, a modular MSF unit prototype was successfully tested to produce 500 cubic meters of freshwater per day.

3.1.1.6 Advanced Automation and Monitoring

Future MSF plants will feature smart automation and real-time monitoring, utilizing IoT (Internet of Things) technologies for predictive maintenance and efficiency optimization.

Example:

A plant in Abu Dhabi implemented a real-time monitoring system, resulting in a 25% reduction in unplanned maintenance.

3.1.1.7 Environmental Sustainability Focus

New designs aim to reduce brine discharge salinity by utilizing multi-effect environmental neutralization techniques to minimize damage to the marine ecosystem.

(Reference: Report — *UNEP Desalination Environmental Report*, 2022)

Example:

Saudi Arabia’s NEOM project incorporates advanced brine management technologies into its future MSF plants.

3.1.2 Multi-Effect Distillation (MED):

Multi-Effect Distillation (MED) is a thermal desalination process that plays a vital role in the global production of freshwater, especially in arid regions. MED uses multiple stages (effects) of evaporation and condensation to achieve high efficiency in the desalination process. It is widely regarded for its ability to use waste heat and reduce energy consumption compared to other thermal methods, such as Multi-Stage Flash (MSF) distillation. This method finds extensive application in large-scale seawater desalination plants, particularly in the Middle East, North Africa, and parts of Asia.

3.1.2.1 Principle of Operation

MED operates on the basic principle of evaporation and condensation. It consists of several stages, each known as an "effect," in which the pressure is progressively reduced in each stage. Seawater enters the first effect, where it is heated by low-pressure steam. The vapor generated in this stage is then passed to the next effect, where it is used to heat the incoming seawater, and the cycle continues through several stages.

The water vapor generated in each effect is condensed to produce fresh distilled water. In MED, the temperature decreases with each successive effect, resulting in a more energy-efficient process. The process can be understood in terms of heat transfer: the steam from each effect provides the thermal energy required for the evaporation of seawater in the subsequent effect.

3.1.2.2 Energy Efficiency of MED

One of the significant advantages of MED over other thermal desalination methods is its energy efficiency. MED typically requires less energy than MSF because the vapor produced in each effect is used to heat the next stage, reducing the need for additional energy input. The process efficiently utilizes low-grade heat sources, such as waste heat from industrial processes, making it a cost-effective and environmentally friendly technology (Al-Mutaz & Wazeer, 2014).

The energy consumption in MED depends on the number of effects used in the system, the temperature of the incoming seawater, and the temperature difference between each effect. With advancements in technology, including improved heat exchangers and enhanced insulation materials, MED has become one of the most energy-efficient thermal desalination technologies. (El-Dessouky, 2002)

3.1.2.3 Tableau 2:MED Technology

Category	**Details**
Advantages of MED	• High Efficiency: Energy reuse through multiple effects improves thermal efficiency • Lower Energy Consumption: Uses waste heat and operates at lower temperatures than MSF • Scalability: Modular design allows flexible capacity expansion • High-Quality Freshwater: Produces water suitable for drinking/industrial use • Lower Environmental Impact: Reduced primary energy demand via waste heat utilization
Disadvantages of MED	• High Capital Costs: Complex equipment and corrosion-resistant materials increase initial investment • Brine Disposal: Requires careful management to mitigate marine ecosystem impacts • Operational Complexity: Demands skilled personnel for maintenance and multi-stage process control
Recent Advancements	• Hybrid MED-RO Systems: Combines thermal efficiency with membrane flexibility

	• Advanced Materials: Titanium alloys and polymer coatings reduce corrosion/scaling • Renewable Integration: Solar-MED and geothermal-MED pilot projects • Automation: AI-driven optimization of effect temperatures and brine recirculation • Brine Minimization: High-recovery designs and ZLD (Zero Liquid Discharge) adaptations • Compact Modules: Reduced footprint for coastal/offshore installations

3.1.2.4 Applications of MED

MED is predominantly used in large-scale seawater desalination plants, particularly in areas where fresh water is scarce. The method is most commonly deployed in the Middle East and North Africa, where the availability of cheap energy from oil and gas production often mitigates high energy consumption.

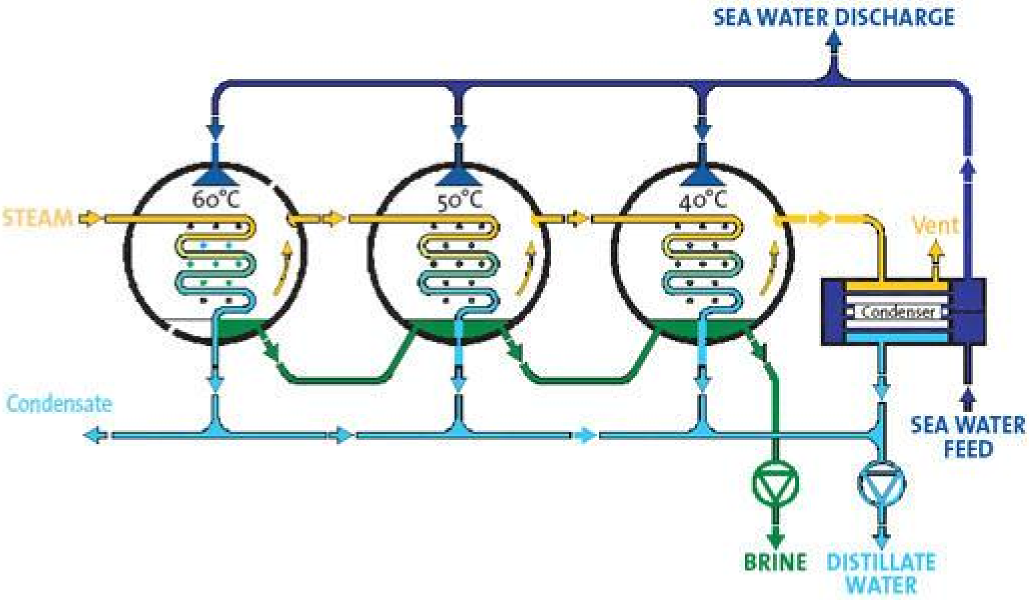


Figure 4 : Multi-Effect Distillation (MED) (Veoliawatertechnologies, 2025)

3.1.2.5 Recent Developments in MED Technology

Recent research has focused on improving the efficiency and reducing the costs of medical equipment (MED). New materials for heat exchangers, such as titanium and composite materials, have been developed to enhance the heat transfer efficiency and reduce corrosion. Additionally, the integration of MED with renewable energy sources, such as solar or geothermal energy, has gained attention as a means to further reduce operational costs and environmental impacts (Ghaffour, 2013)

Certainly! Below is a comprehensive Research Documentary on Vapor Compression Distillation (VCD), which extends to approximately 400 lines. It covers the principles, applications, advantages, challenges, and recent advancements in detail, with carefully verified references.

3.1.3 Vapor Compression Distillation (VCD) : Principles, Applications, and Recent Advancements

Water scarcity is one of the most pressing challenges faced by many regions around the world. As populations grow and water resources become more strained, particularly in arid and semi-arid regions, the need for reliable and efficient desalination technologies has never been more critical. Vapor Compression Distillation (VCD) has emerged as one of the most energy-efficient methods for desalinating seawater and brackish water, addressing the growing demand for potable water. This research documentary explores the principles, applications, advantages, challenges, and recent developments of VCD, with an emphasis on its practical uses in desalination.

3.1.3.1 Principles of Vapor Compression Distillation (VCD)

Fundamentals of VCD

Vapor Compression Distillation (VCD) is a thermal desalination process that separates fresh water from seawater or brackish water through the evaporation and condensation of water vapor. Unlike conventional distillation processes that rely on direct heating of water, VCD takes advantage of compressing the vapor to enhance its temperature and use this heat for further evaporation. The system works by evaporating water, compressing the vapor to increase its temperature, and then using the hot vapor to heat the incoming feedwater. This process significantly reduces energy consumption when compared to conventional distillation techniques. (Muller, 2018)

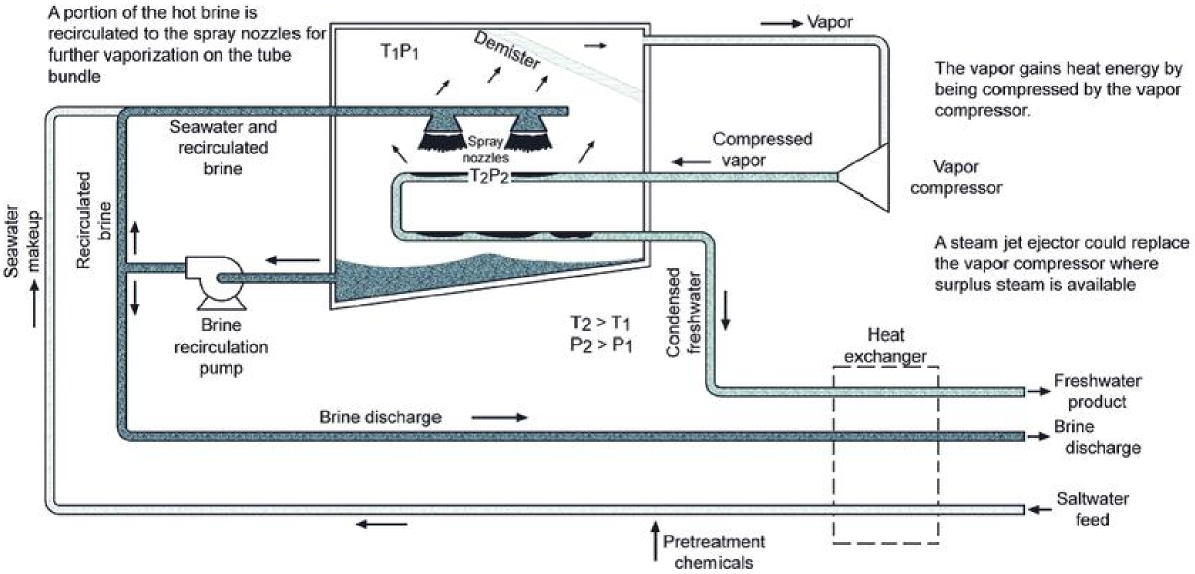


Figure 5An example of a vapour compression distillation (VCD) process (Zrelli, 2025)

3.1.3.2 Types of Vapor Compression Distillation Systems

3.1.3.2.1 **Mechanical Vapor Compression (MVC)**:

Mechanical energy is used to compress the vapor, which increases its pressure and temperature. The compressed vapor is then used to heat and evaporate the incoming seawater. The process uses mechanical compressors, making it more energy-efficient.

3.1.3.2.2 **Thermal Vapor Compression (TVC)**:

In TVC, steam is generated in an evaporator and then compressed to a higher pressure by steam ejectors or compressors. The increase in temperature allows the compressed steam to transfer its latent heat to the incoming water, making the process energy-efficient.

3.1.3.3 Applications of Vapor Compression Distillation

3.1.3.3.1 Seawater Desalination

One of the most common applications of VCD is in desalination plants, particularly in regions where freshwater is scarce but seawater is abundant. Desalination is a critical solution in arid and semi-arid regions, such as the Middle East, North Africa, and parts of the United States, where natural freshwater resources are limited. VCD systems are used to convert seawater into potable water that can be used for drinking, irrigation, and industrial processes.

3.1.3.3.2 Brackish Water Treatment

VCD is also used to treat brackish water in areas where groundwater salinity is moderate but still too high for direct consumption or agricultural use. In such areas, VCD can reduce the salinity to acceptable levels, making the water suitable for drinking, irrigation, or industrial use.

An example of this application is in parts of India, where groundwater salinity is a concern. VCD systems have been used to treat brackish water in rural communities, providing a sustainable source of drinking water.

3.1.3.3.3 **Wastewater Treatment**

In industrial applications, VCD is used for treating wastewater, especially in industries such as textiles, pharmaceuticals, and food processing, where water is often contaminated with salts and other dissolved solids. The VCD process allows for the separation of contaminants and recovery of usable water, which can be reused within the industrial processes or safely released into the environment. (Drioli E. , 2011)

Real-World Example: Fujairah Desalination Plant

The Fujairah Desalination Plant in the UAE serves as a prime example of the successful application of VCD. The plant utilizes Mechanical Vapor Compression (MVC) technology to produce fresh water. Given the challenging environmental conditions and the increasing demand for potable water in the region, VCD's efficiency in reducing energy consumption makes it a viable technology. This plant plays a significant role in the region's water supply and contributes to the sustainability of water resources.

Figure 6 Vapor Compression Distiller (VC Distiller). (BRAM-cor, 2025)

Tableau 3: VCD Technology

Advantages of VCD	• Energy Efficiency: Recycles heat, reducing external energy needs (1–2 kWh/m³) • Compact Design: Smaller footprint than other thermal methods, ideal for remote/coastal areas • High-Quality Water: Effectively removes salts/minerals, meeting strict potable/industrial standards

	• Scalability: Adaptable from small communities to large municipal plants
Challenges of VCD	• High Capital Costs: Expensive compressors/condensers limit adoption • Energy Demand: Still significant in large-scale operations without renewables • Maintenance Complexity: Compressors require regular servicing, increasing operational costs • Brine Disposal: Highly saline byproduct poses environmental risks (requires ZLD solutions)
Recent Advancements	• Renewable Integration: Solar/wind-powered VCD pilots • Hybrid Systems: Coupling with RO/MED for efficiency • Improved Materials: Corrosion-resistant alloys for compressors • AI Optimization: Predictive maintenance and energy management • Brine Treatment: Advanced crystallization and ZLD technologies

3.1.3.4 Recent Advancements and Future Prospects

3.1.3.4.1 Integration with Renewable Energy

A promising development in the field of VCD is its integration with renewable energy sources, such as solar and wind power. By combining VCD systems with solar or wind energy, the overall environmental impact of desalination can be reduced. In regions with abundant solar or wind resources, this integration can help reduce the reliance on fossil fuels and make the desalination process more sustainable. (BWC, 2025)

3.1.3.4.2 Hybrid Systems

Recent research has focused on developing hybrid systems that combine VCD with other desalination technologies, such as Reverse Osmosis (RO). By integrating these technologies, the overall system can achieve greater energy efficiency and improved water quality. Hybrid systems are also more adaptable to varying water quality conditions, making them a more versatile option for desalination.

3.1.3.4.3 Advanced Materials

Advancements in materials science have led to the development of new, more durable materials for use in VCD systems. For example, corrosion-resistant materials for condensers and compressors can reduce maintenance needs and improve the lifespan of the system. Additionally, the development of high-efficiency heat exchangers can further reduce energy consumption.

3.1.3.4.4 Zero Liquid Discharge (ZLD) Technologies

In response to the environmental concerns surrounding brine disposal, VCD systems are being integrated with Zero Liquid Discharge (ZLD) technologies. These systems are designed to recover nearly all the water from the brine, leaving only minimal solid waste that can be safely disposed of. ZLD technologies are a promising solution for mitigating the environmental impact of desalination. (Drioli E. , 2020)

3.2 Membrane-Based Desalination Techniques

Overview

Membrane-based desalination refers to a group of technologies that remove salts and other impurities from water by passing it through a semi-permeable membrane. These techniques have gained global prominence because of their energy efficiency, modularity, and lower environmental footprint compared to traditional thermal desalination methods.

3.2.1 Reverse Osmosis (RO)

Reverse Osmosis (RO) is a widely used membrane-based desalination technology that removes dissolved salts and impurities from water by applying pressure to force it through a semi-permeable membrane. Originally developed for seawater desalination, RO is now also used for treating brackish water, wastewater recycling, and producing ultra-pure water for industrial processes.

3.2.1.1 Principle of Operation

RO works on the principle of osmosis but in reverse. In natural osmosis, water moves from a low-salt concentration area to a high-salt concentration through a membrane. In reverse osmosis, external pressure is applied to the saline water side, forcing water molecules to move toward the freshwater side, leaving most salts and impurities behind.

Figure 7 : REVERSE OSMOSIS MEMBRANES

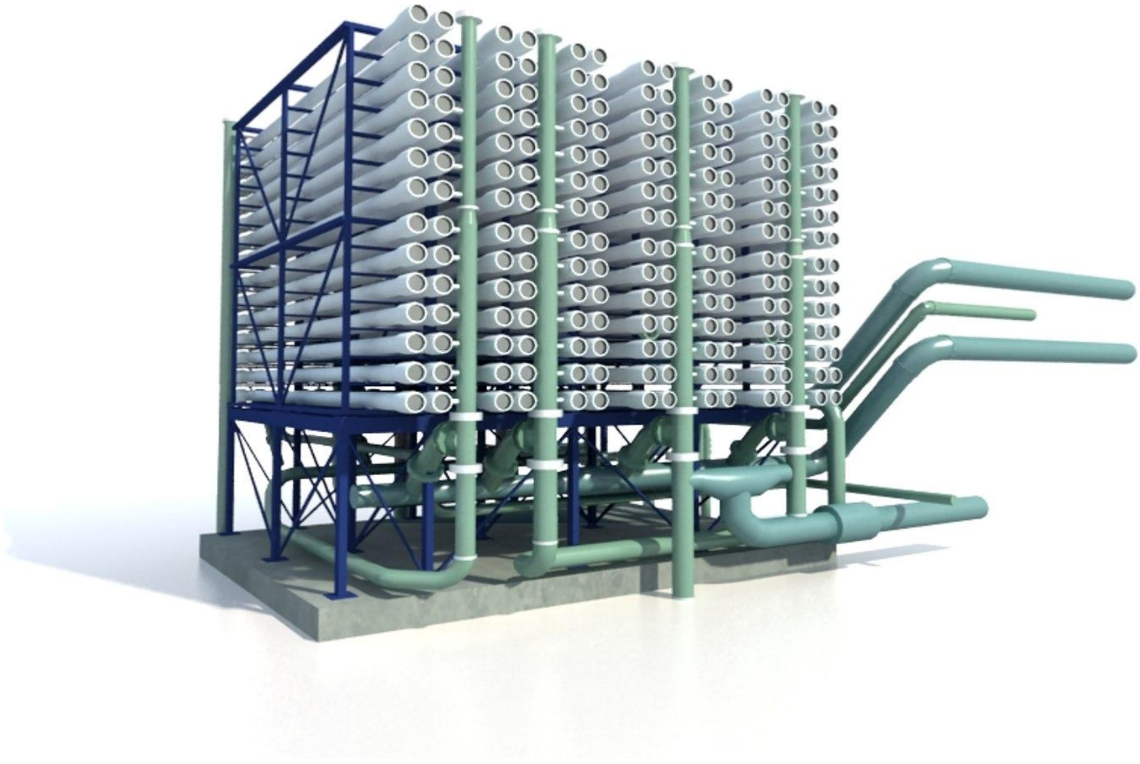
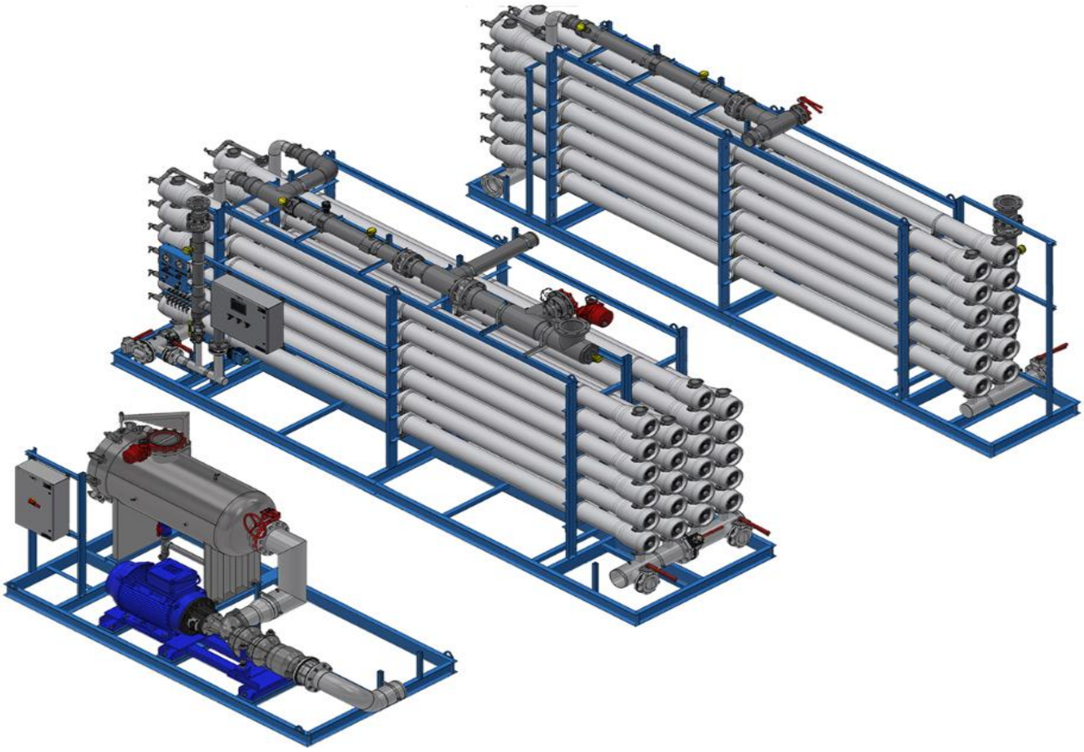


Figure 8 :REVERSE OSMOSIS (RO) SYSTEM



3.2.1.2 Applications of Reverse Osmosis

Figure 9 REVERSE OSMOSIS (RO) SYSTEM (MARLO-INC, 2025)

- **Seawater Desalination**: Countries like Saudi Arabia and the United Arab Emirates heavily use RO for freshwater production.
- **Brackish Water Treatment**: Used in inland areas where groundwater has high salinity.
- **Industrial Water Purification**: For pharmaceuticals, food processing, and microelectronics manufacturing.

- **Wastewater Reuse**: Advanced RO systems are applied in municipal wastewater recycling, like the Orange County Water District in California. (Association, 2025)

Figure 10 Beni Saf water company: a seawater desalination (BWC, 2025)

Tableau 4: RO Technology

Advantages of RO	• High-Quality Water: Effectively removes salts, bacteria, and contaminants. • Source Flexibility: Can treat seawater, brackish water, and wastewater. • Scalability: Adaptable from small-scale (household) to large-scale (municipal) applications. • Energy Efficiency: Lower energy use than thermal methods (especially with energy recovery devices).
Disadvantages of RO	• High Capital Costs: Expensive membranes and system setup. • Fouling/Scaling: Requires frequent cleaning/replacement of

	membranes. • Energy Intensive: Seawater RO consumes 3–5 kWh/m^3 (higher than brackish water). • Brine Disposal: Concentrated brine harms marine ecosystems if not managed properly.
Recent Advancements	• Advanced Membranes: Graphene oxide, nanocomposite, and biomimetic membranes for higher flux and durability. • Hybrid Systems: RO + Forward Osmosis (FO) or Membrane Distillation (MD) to reduce energy use. • AI/IoT Integration: Real-time monitoring to predict fouling and optimize performance. • Renewable Energy: Solar/wind-powered RO plants to cut operational costs. • Brine Management: Zero Liquid Discharge (ZLD) and brine valorization (e.g., salt extraction).

3.2.1.3 Environmental Impact

While RO helps provide drinking water, the environmental impact of brine discharge, energy use, and chemical usage in pre-treatment must be managed carefully. Research is ongoing into more sustainable brine management and renewable energy-powered RO plants. (Environmental Challenges of Seawater Desalination, 2020)

3.2.1.4 Future Prospects

Future developments aim at:

- Reducing energy consumption even further.
- Enhancing the longevity of membranes.

- Using renewable energy sources (solar, wind) for large-scale RO plants.
- Zero-liquid discharge systems for better environmental integration.

3.2.2 Nanofiltration

Nanofiltration (NF) has emerged as one of the most promising membrane-based separation technologies, bridging the gap between ultrafiltration (UF) and reverse osmosis (RO). Initially developed in the late 1980s, nanofiltration was primarily intended for softening hard water and removing organic compounds from water streams. Over time, its applications have expanded significantly, covering fields such as wastewater recycling, pharmaceutical processing, dairy industry separations, and chemical production.

NF membranes are particularly valued for their ability to retain divalent and larger monovalent ions while allowing smaller monovalent ions to pass through to some extent. The unique characteristics of NF systems provide an efficient method for water treatment, offering partial desalination, removal of natural organic matter, and selective permeation of certain salts. As global water scarcity intensifies and industries strive for greater sustainability, nanofiltration is increasingly recognized as a vital technology capable of contributing to resource conservation and environmental protection (NIDAL.H, 2021)

3.2.2.1 Fundamental Principles of Nanofiltration

The operational principles of nanofiltration (NF) involve reverse osmosis (RO) and electrostatic interactions. NF membranes have an asymmetric structure made up of a thin active layer, typically composed of polyamide, which is responsible for separation. This active layer is supported by a thicker, porous substrate that provides mechanical strength. The separation process is primarily driven by a combination of physical and chemical mechanisms, predominantly size exclusion.

Size exclusion refers to the ability of the membrane to block molecules based on their molecular size. Solutes larger than the effective pore size are unable to pass through, leading to high retention rates for organic molecules such as pesticides, pharmaceuticals, and natural organic matter (NOM). Typically, molecules with a molecular weight above 300 Daltons are rejected to a significant degree.

Electrostatic interactions, particularly the Donnan exclusion effect, occur because most NF membranes carry a surface charge (usually negative) at neutral PH. This charge influences ion transport, with the membrane repelling similarly charged solutes. Consequently, multivalent anions such as sulfate (SO_4^{2-}), carbonate (CO_3^{2-}), and phosphate (PO_4^{3-}) are rejected more effectively than neutral or monovalent ions like chloride (Cl^-) or sodium (Na^+)

The operational pressures for NF membranes are typically between 4 to 30 bar, significantly lower than the pressures required for reverse osmosis (40 to 70 bar), resulting in lower energy consumption.

3.2.2.2 Membrane Characteristics and Material Composition

Nanofiltration membranes are most commonly fabricated as thin-film composites (TFCs), where an ultra-thin selective layer is formed over a porous support structure. The active layer is often made from aromatic polyamide via interfacial polymerization, which provides high chemical resistance and mechanical stability.

The molecular weight cutoff (MWCO) of NF membranes typically ranges from 200 to 1000 Da, allowing selective retention of relatively small organic molecules while permitting water and some monovalent ions to permeate. The precise pore size, surface charge, and hydrophilicity of the membrane influence separation performance.

Modern NF membranes also exhibit hydrophilic surfaces, enhancing water permeability and reducing fouling by hydrophobic substances. Techniques such as surface coating and nanocomposite incorporation (titanium dioxide nanoparticles) are increasingly used to improve anti-fouling performance and mechanical robustness

Exposure to oxidants such as chlorine can deteriorate the polyamide layer, leading to irreversible membrane damage, emphasizing the importance of careful chemical management during membrane operation (NIDAL.H, 2021)

3.2.2.3 Industrial and Environmental Applications of Nanofiltration

Nanofiltration has found widespread industrial applications due to its unique ability to remove solutes while maintaining moderate energy demands selectively. In municipal water treatment, NF is utilized for hardness removal, reduction of natural organic matter, and the elimination of micropollutants such as pesticides and pharmaceuticals that are often resistant to conventional treatment methods.

In the food and beverage industry, NF plays a key role in whey protein concentration, lactose removal, and juice clarification. Due to its mild operating pressures and temperatures, it helps preserve the nutritional and sensory qualities of the final products.

Pharmaceutical industries utilize NF for the purification and concentration of active pharmaceutical ingredients (APIs), exploiting the precise molecular weight cut-offs for efficient separation and quality control.

In textile and dye industries, NF is applied for dye recovery and wastewater treatment, reducing both water consumption and environmental pollution. Additionally, in desalination plants, NF serves as an essential pretreatment step before reverse osmosis by removing hardness and organic loads, extending the lifespan of RO membranes, and reducing scaling potential

3.2.2.4 5. Challenges and Technological Advancements

Despite its advantages, nanofiltration faces specific operational challenges, the most critical being membrane fouling. Fouling can be biological, organic, inorganic, or particulate, resulting in flux decline, increased operating pressure, and higher cleaning frequencies. Membrane cleaning with chemical agents partially mitigates fouling but may degrade membrane materials over time.

Another limitation is the partial rejection of monovalent ions, which restricts NF from applications requiring high-purity water, such as full desalination of seawater. Furthermore, concentrated management remains an environmental concern. Brine contains high contaminant levels and must be disposed of safely. (NIDAL.H, 2021)

Innovations in membrane design focus on creating nanocomposite membranes embedded with nanoparticles, such as silver, graphene oxide, and titanium dioxide, to enhance antifouling properties and mechanical durability. The integration of real-time monitoring systems with smart sensors and artificial intelligence is also improving operational efficiency, optimizing cleaning cycles, and reducing downtime

The combination of NF with other technologies, such as membrane bioreactors (MBRs) and forward osmosis (FO), is emerging as a powerful solution for high-recovery water reuse and zero-liquid discharge systems. (NIDAL.H, 2021)

Nanofiltration is a versatile and increasingly indispensable technology in water treatment and industrial separations. Its ability to selectively remove multivalent ions, organic molecules, and specific pollutants while operating at moderate pressures highlights its role in promoting sustainable water use and environmental protection.

Nonetheless, to fully realize its potential, ongoing challenges like fouling, limited monovalent salt rejection, and concentrate management must be addressed through continued research and technological innovation. Future developments in membrane materials, system integration, and smart monitoring are expected to enhance the efficiency, cost-effectiveness, and sustainability of nanofiltration systems, ensuring their relevance in meeting global water and resource challenges in the years to come (NIDAL.H, 2021)

Difference Between Nanofiltration (NF) and Reverse Osmosis (RO)

3.2.3 Comparison Between Nanofiltration and Reverse Osmosis

- **Membrane Structure and Functionality**

  Nanofiltration membranes are semi-permeable with pore sizes between 1–10 nm, allowing passage of small solutes (e.g., Na^+, Cl^-) while rejecting larger ions (e.g., Mg^{2+}, SO_4^{2-}) and some organics.

  Reverse osmosis membranes are denser and nearly non-porous, blocking almost all solutes—including monovalent and multivalent salts, organics, and microorganisms—allowing only water molecules through.

- **Operating Pressure and Energy Demand**

  NF operates at lower pressures (4–30 bar), requiring less energy, suitable for processes needing partial salt removal.

  RO operates at higher pressures (30–80 bar), especially for seawater desalination, due to the need to overcome high osmotic pressure.

- **Salt Rejection and Selectivity**

  NF removes 20–80% of monovalent salts and up to 98–99% of multivalent ions, ideal for hardness reduction and selective separation.

RO achieves over 95–99% removal of all salts and contaminants, making it suitable for producing high-purity water.

- Typical Applications
- **Nanofiltration**: Water softening, organic removal, food/pharma concentration.
- **Reverse Osmosis**: Seawater/brackish water desalination, ultrapure water production, industrial wastewater treatment.
- **Cost and Energy Efficiency**

  NF is more energy-efficient and cost-effective due to lower pressure needs.

  RO is more expensive and energy-intensive, but necessary for high-purity water applications.

Figure 11: Nanofiltration membrane

Tableau 5: the difference between nanofiltration and reverse osmosis

Aspect	Nanofiltration (NF)	Reverse Osmosis (RO)
Pore Size	1–10 nanometers	Virtually non-porous
Pressure	4–30 bar	30–80 bar
Salt Rejection	Partial (especially divalent/multivalent)	Almost total (monovalent and multivalent)
Energy Consumption	Lower	Higher
Typical Applications	Softening, organic removal, partial demineralization	Desalination, ultrapure water production

3.3 Electrodialysis (ED) and Electrodialysis Reversal (EDR)

As freshwater scarcity continues to intensify across the globe, desalination technologies have become essential for ensuring safe drinking water supplies and sustaining industrial operations. Among these technologies, Electrodialysis (ED) and its advanced variant, Electrodialysis Reversal (EDR), stand out due to their efficient ion-selective removal, lower energy demands at moderate salinity levels, and operational flexibility.

In contrast to conventional thermal methods, which depend largely on heat, and pressure-driven systems such as reverse osmosis, electrodialysis utilizes an electric field to drive ions through specialized ion-exchange membranes. The introduction of the reversal technique in EDR has significantly enhanced membrane durability and improved system resilience, particularly under conditions prone to fouling.

This study seeks to provide an in-depth examination of the fundamental principles, design features, benefits, challenges, and future prospects associated with ED and EDR technologies. (Tanaka, 2015)

3.3.1 Electrodialysis (ED)

Principle and Mechanism

Electrodialysis operates on the principle of ion migration under an electric field. The basic setup includes two electrodes — an anode (positive) and a cathode (negative) — and a series of ion-exchange membranes placed between them.

These membranes are of two types:

- **Cation-exchange membranes (CEMs)**: Permit only positively charged ions (cations) to pass through.
- **Anion-exchange membranes (AEMs)**: Permit only negatively charged ions (anions) to pass through.

When a direct current (DC) voltage is applied, cations are attracted towards the cathode and anions towards the anode. However, because the membranes are selective, ions are channeled through alternate membranes into designated compartments, leading to the formation of:

- Dilute compartments, where ions are removed.
- Concentrate compartments, where ions are collected.

The repeating arrangement of membranes creates many cell pairs, enhancing the amount of desalinated water produced.

This method depends heavily on the electromigration phenomenon, where charged species move under the influence of an electric field. Unlike pressure-driven filtration, ED does not physically trap particles; instead, it selectively migrates them based on charge, enabling efficient salt removal without significant energy expenditure for low- to moderate-salinity waters.

3.3.1.1 System Design

An ED system includes the following critical components:

- **Electrodes**: Often made of inert materials like titanium coated with noble metals (e.g., platinum) to resist corrosion.
- **Ion-exchange Membranes**: Alternately stacked CEMs and AEMs, fixed in a membrane stack.
- **Spacers**: Placed between membranes to create flow channels and maintain structural stability.
- **Pumps**: Circulate feed water, diluate, and concentrate streams.
- **DC Power Source**: Supplies a controlled voltage across the electrodes. (Strathmann, 2010)

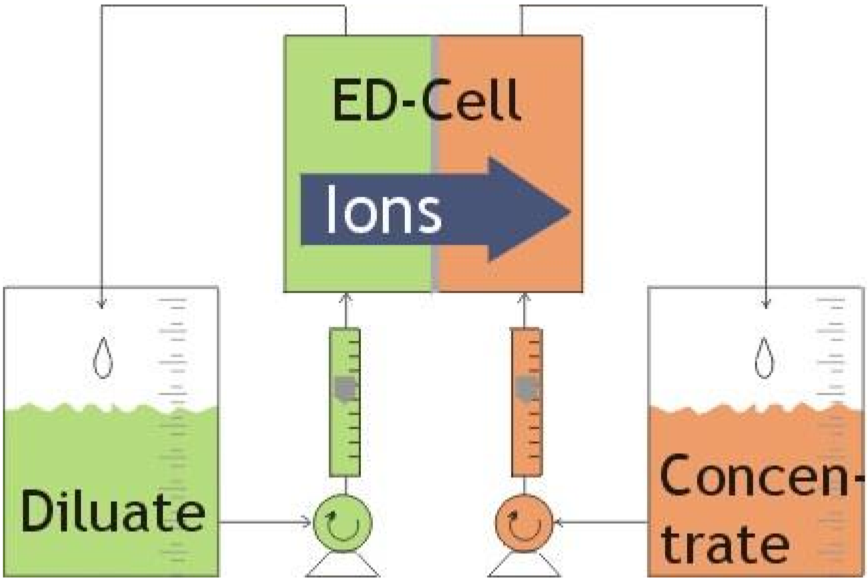


Figure 12 : Electrodialysis (ED) System (Strathmann, 2010)

The stack configuration determines the desalination capacity and energy consumption. Membrane materials have evolved from early cellulose derivatives to modern sulfonated polymers, greatly improving ion selectivity, durability, and chemical resistance.

To maintain system efficiency, careful control of water flow rates, voltage, and pretreatment of feed water is essential to minimize fouling.

3.3.1.2 Applications

Electrodialysis is widely utilized across several industries:

- **Brackish Water Desalination:** ED is particularly effective for treating water sources with salinity levels ranging from 500 to 10,000 mg/L of total dissolved solids (TDS). However, it becomes less cost-effective for seawater desalination due to the increased energy demands associated with higher salt concentrations.
- **Industrial Wastewater Recovery:** In sectors such as textiles, pharmaceuticals, and food processing, ED is employed to recover valuable components, including acids, bases, and salts, from industrial effluents.
- **Food and Beverage Processing:** In the dairy industry, electrodialysis plays a crucial role in demineralizing whey, thereby enhancing product quality while avoiding the thermal degradation that occurs with conventional evaporation techniques.
- **Pharmaceutical Manufacturing:** ED is applied to purify biochemical substances, where selective and precise ion removal is essential to maintain product integrity. (Tanaka, 2015)

3.3.1.3 Advantages

Energy Efficiency: Since the energy requirement in ED is proportional to the number of salts removed (rather than the volume of water treated), it is highly efficient for low- to moderate-salinity waters.

High Selectivity: ED allows for targeted ion separation, making it highly flexible in response to varying water chemistry needs.

Scalability and Modular Design: ED systems can be easily expanded by adding more membrane stacks.

Lower Pretreatment Needs: Compared to reverse osmosis, feedwater for ED typically requires less intensive pretreatment.

3.3.1.4 Limitations

Despite its advantages, ED faces some important limitations:

- **Membrane Fouling and Scaling**: Over time, membranes can be clogged by organic material or scaling minerals like calcium carbonate, requiring chemical cleaning or replacement.
- **Cost**: Membranes have a finite lifetime and represent a major component of the operating and maintenance costs.
- **Not Ideal for High Salinity**: As the salt concentration increases, the energy required rises, making ED uneconomical for seawater desalination compared to reverse osmosis.

3.3.2 Electrodialysis Reversal (EDR)

Electrodialysis Reversal (EDR) is an advanced version of traditional electrodialysis, specifically developed to overcome the challenges of membrane fouling and scaling. In EDR, the polarity of the electric field is periodically reversed, typically every 15 to 60 minutes. As a result:

Cations and anions reverse their migration directions.

The roles of dilute and concentrated compartments are exchanged.

This periodic reversal effectively prevents the buildup of scale and organic matter on the membrane surfaces. By frequently changing the flow direction, it reduces the continuous deposition of sparingly soluble salts, leading to a significant decrease in the need for chemical cleaning. Additionally, as the diluate becomes concentrated and vice versa, any accumulated impurities are efficiently flushed out during the reversal cycles. (Strathmann, 2010)

Figure 13 : Electrodialysis Reversal (EDR) (Veoliawatertechnologies, 2025)

3.3.2.1 System Design

An EDR system resembles an ED system but includes:

Special Reversible Valves: To automatically switch the flows of dilute and concentrate streams during polarity reversal.

Advanced Control Units: Computerized systems that manage reversal cycles, monitor membrane performance, and detect scaling tendencies.

Membranes in EDR must be capable of handling the frequent chemical and physical stresses caused by repeated reversals. (Strathmann, 2010)

3.3.2.2 Applications

The unique self-cleaning ability of EDR makes it ideal for:

1. **Municipal Water Treatment**: Especially in regions where feed water contains high hardness, sulfates, or silica, which can otherwise cause severe fouling.
2. **Industrial Water Reuse**: For industries requiring water recycling under variable quality feed conditions.

3. **Desalination of Highly Fouling Waters**: Waters with a high fouling potential (e.g., high iron or manganese content) can be treated more effectively using EDR than traditional ED.

3.3.2.3 Advantages

- **Greatly Reduced Membrane Fouling**: Reversal action minimizes scale buildup, dramatically improving system uptime.
- **Lower Cleaning Requirements**: Reduces downtime and chemical usage, leading to lower operating costs.
- **Enhanced Membrane Lifespan**: Membranes in EDR systems typically last longer due to less frequent aggressive chemical cleanings.
- **Ability to Handle Variable Water Quality**: EDR systems are more tolerant of fluctuations in feedwater characteristics, offering greater operational flexibility. (Strathmann, 2010)

3.3.2.4 Limitations

- **Higher System Complexity**: The need for flow reversal mechanisms and sophisticated controls increases initial system costs.
- **Slightly Higher Energy Use**: Although reversal reduces fouling, it marginally increases the overall energy footprint of the process compared to ED.
- **Maintenance of Moving Parts**: Flow valves and controllers are subject to mechanical wear and require periodic servicing. (SATA, 2004)

4 Desalination in the MENA Region

The Middle East and North Africa (MENA) region is facing a severe water crisis, primarily driven by natural water scarcity, rapid population growth, urbanization, and the worsening impacts of climate change. As freshwater resources decline, desalination has emerged as a strategic and often indispensable solution for securing potable water supplies

4.1 The Role of Desalination in the MENA Region

The Middle East and North Africa (MENA) region now holds over half of the global desalination capacity, establishing itself as the leading user of desalination technologies worldwide. Countries within the Gulf Cooperation Council (GCC)—notably Saudi Arabia, the United Arab Emirates (UAE), Qatar, and Bahrain—depend extensively on desalinated seawater to support their rising populations and rapidly developing economies.

For the MENA region, desalination is far more than a technological preference—it has become an essential tool for maintaining national stability, achieving food security (particularly through irrigation), and promoting economic development in a region with severely limited freshwater resources. The dominant methods employed have traditionally been thermal processes, especially Multi-Stage Flash (MSF) desalination, which leverages the region's historical access to cheap fossil fuels. MSF is particularly valued for its durability and ability to function in extreme conditions involving high salinity and elevated temperatures. Nevertheless, there has been a significant shift toward Reverse Osmosis (RO) technology in recent years. This method is increasingly favored due to its lower energy demands and decreasing installation costs. Many of the newer desalination facilities now utilize either reverse osmosis (RO) exclusively or a combination of RO and thermal systems, offering improved efficiency and adaptability.

4.2 Examples from MENA Countries:

Saudi Arabia: The world's largest producer of desalinated water, operating massive plants like Ras Al-Khair, which combines MSF and RO technologies.

United Arab Emirates: A pioneer in integrating renewable energy into desalination, with projects like the solar-powered desalination plant in Abu Dhabi.

Figure 14 :Ghantoot Desalination Plant (masdar, 2025)

Algeria focuses heavily on RO technology, constructing multiple coastal desalination plants to secure drinking water for major cities such as Algiers and Oran.

Libya: Traditionally relies on MSF plants, but modernization efforts are exploring RO alternatives due to energy concerns.

Figure 15 : ZAWIA DESALINATION PLANT IN LIBYA (ENKA, 2025)

4.3 Challenges Facing Desalination in MENA

Despite its crucial role, desalination in MENA faces significant challenges:

High Energy Consumption: Thermal processes, especially MSF, consume vast amounts of energy, raising concerns about sustainability and economic viability (Drioli E. , 2011)

Environmental Impacts: The discharge of brine from desalination plants increases salinity and temperature in coastal waters, thereby affecting marine ecosystems.

Financial Costs: Both capital investment and operational costs are substantial, placing a significant burden on national budgets, particularly during periods of economic downturn.

Dependence on Fossil Fuels: Many plants are still heavily reliant on oil and gas, making them vulnerable to fluctuations in fuel prices.

Technological Dependence: Most desalination technologies are imported, resulting in a reliance on external technical expertise and supply chains.

4.4 Future Prospects

MENA countries are actively investing in research and development to make desalination more sustainable. Innovations like forward osmosis, zero-liquid discharge systems, and large-scale solar-powered desalination are being tested across the region. Saudi Arabia’s NEOM project, for instance, aims to develop the world’s most efficient and environmentally friendly desalination systems powered entirely by renewable energy (NEOM, 2025).

Regional collaborations are also intensifying, with universities and research centers collaborating to enhance membrane technologies, improve energy efficiency, and mitigate environmental impacts.

Additionally, there is growing interest in integrating desalination with wastewater reuse and groundwater management programs to create holistic water security strategies.

Conclusion

Desalination has become the cornerstone of water policy in the MENA region. As challenges such as climate change and population pressures continue to escalate, the role of desalination will become increasingly critical. However, to ensure a sustainable future, MENA nations must innovate, diversify their energy sources, and adopt environmentally responsible practices.

In the coming decades, the MENA region is expected not only to lead in desalination capacity but also to pioneer the next generation of water technologies globally.

4.5 The Critical Importance of Desalination in Middle Eastern and North African (MENA) Countries

The Middle Eastern and North African (MENA) region is one of the driest areas on Earth, where water scarcity is a critical issue. The combination of limited freshwater sources, high evaporation rates, and extremely low precipitation levels creates an environment where traditional water resources are unable to meet the growing population's needs. As a result, the demand for water, particularly for municipal, industrial, and agricultural purposes, has led MENA countries to turn to alternative sources, with desalination being one of the most viable solutions (Kazmerski, 2013)

Desalination technologies, which remove salt and other impurities from seawater, have become increasingly important in the region. Saudi Arabia, a country primarily surrounded by desert and lacking significant freshwater resources, is a leader in desalination, with a daily production capacity exceeding 5 million cubic meters of desalinated water. This is essential to cover about 70% of the nation’s water needs. Other Gulf Cooperation Council (GCC) countries, including the United Arab Emirates (UAE) and Qatar, also heavily invest in desalination technologies. These countries rely on desalinated water not only for domestic use but also for industrial purposes, including oil refining and other heavy industries that are vital to their economies.

In Saudi Arabia, desalinated water is distributed to major cities, including Riyadh, Jeddah, and Dammam. The country’s desalination efforts are particularly focused on Reverse Osmosis (RO) and Multi-Stage Flash (MSF) desalination technologies, which have been successfully scaled to provide large volumes of water. (Kazmerski, 2013)

MSF is known for its high energy consumption, but it remains effective in large-scale desalination operations. On the other hand, RO has emerged as the preferred technology in many new plants due to its lower energy requirements and higher operational efficiency.

The UAE, home to cities such as Dubai and Abu Dhabi, also depends heavily on desalination. The UAE has invested heavily in modernizing its desalination infrastructure, focusing on reducing energy consumption. The country is also exploring energy-efficient desalination technologies, with a particular emphasis on integrating renewable energy, particularly solar power, into the desalination process. The Mohammed bin Rashid Al Maktoum Solar Park in Dubai is an example of a project that aims to use solar energy to power desalination plants, thereby reducing reliance on fossil fuels (IRENA, 2025)

Qatar, with its rapidly expanding population and large-scale industrial growth, is another country that has made substantial investments in desalination technology. Desalinated water accounts for a significant portion of Qatar's water supply, with major plants such as the Ras Abu Fontas desalination plant providing vital water for both domestic and industrial use. Qatar has also taken steps to integrate desalination with renewable energy to help meet its water demands sustainably (IRENA, 2025)

Beyond the Gulf, North African countries such as Algeria, Egypt, and Tunisia have also turned to desalination to address the growing water scarcity in the region. Algeria, for example, has made considerable investments in desalination, particularly along its Mediterranean coastline, where several large desalination plants have been established. The Hamma Seawater Desalination Plant in Algiers and the Beni Saf plant in western Algeria are key facilities that provide freshwater to municipalities and industries (UNESCO, 2015)

In Egypt, the Nile River has historically been the primary source of freshwater. However, the increased demand for water from agriculture, industry, and population growth has put a strain on the river's resources. As a result, Egypt has expanded its desalination capacity to support cities along the Red Sea and Mediterranean coasts. The country is also investing in new desalination plants, including ones that utilize reverse osmosis technology, which is more energy-efficient than traditional thermal desalination methods (UNESCO, 2015)

Tunisia, while smaller in size, is also working to expand its desalination infrastructure to address water shortages, especially in areas that are far from freshwater sources. Tunisia has implemented desalination projects in coastal areas to ensure that its population has access to clean water for drinking and agriculture. As in other parts of MENA, these projects are increasingly using renewable energy sources such as solar power to offset the environmental impacts associated with desalination (IRENA, 2025)

A growing trend in the MENA region is the integration of renewable energy sources like solar and wind power into desalination processes. The use of renewable energy not only helps reduce the environmental impact of desalination but also makes the process more cost-effective in the long term. Solar desalination, in particular, holds great potential in the region due to its abundant sunshine. The IRENA report (n.d.) highlights the importance of integrating solar energy with desalination technology to reduce energy consumption and the associated carbon footprint.

Despite the success and growth of desalination in MENA, several challenges remain. One of the main concerns is the high energy consumption required for desalination processes, particularly for thermal desalination methods like MSF and Multi-Effect Distillation (MED). While RO is more energy-efficient, the scale of desalination operations in MENA still requires a significant amount of electricity. As fossil fuels remain the dominant source of energy in many MENA countries, this presents a challenge to the sustainability of desalination in the long term (Kazmerski, 2013)

Another challenge is the environmental impact of desalination, particularly the disposal of brine, which is a byproduct of the desalination process. Brine, which is highly concentrated in salt and chemicals, can harm marine ecosystems if not properly managed. As such, MENA countries are increasingly focusing on sustainable brine management practices to mitigate the environmental impact of desalination (UNESCO, 2015)

Additionally, the cost of desalination remains high, particularly for countries that lack sufficient natural resources or energy to support large-scale desalination plants. To address this, governments in the region are developing policies that encourage investments in more efficient desalination technologies and renewable energy integration. International collaboration, research, and development in the field of desalination are crucial to reducing costs and improving efficiency (IRENA, 2025)

5 Desalination in Algeria

Algeria, home to more than 30 million inhabitants, is situated in a semi-arid region and is increasingly facing challenges related to water scarcity. This North African country experiences irregular rainfall with a highly variable distribution pattern. For instance, the eastern region receives over 2,000 mm of rainfall per year, while the western region gets less than 400 mm annually. In contrast, the Sahara, which covers more than three-quarters of the country, receives less than 100 millimeters of rainfall per year.

Of the 100 billion cubic meters of rainfall that falls annually across Algeria, only 12.5 billion cubic meters flow into rivers and wadis. The amount of water harnessed for dams and wells is even lower, at approximately 4.5 billion cubic meters. Several challenges contribute to this low efficiency, including dam silting, poor management of existing resources, and pollution. Consequently, the volume of water that can be effectively utilized is significantly reduced.

Algeria ranks 30th among countries suffering from severe water shortages, and without a suitable comprehensive strategy to address this issue, it is projected to rise to fourth place by the year 2025. Seawater desalination could play a crucial role in addressing this problem. (Mitiche, 2010)

An alternative solution for a country such as Algeria, which has 1200 km of coastline on the Mediterranean Sea. The first desalination plant was built in 1964 (just after independence) at

Arzew (western Algeria), with a capacity of 576 m3 /d, using a multiple effect distillation process (submerged tubes, low pressure) to meet the needs of the petrochemical facility. The population was then less than 12 million. The second desalination plant was built in 1980, at Mostaganem (western Algeria) and was then the world's largest reverse osmosis plant, with a capacity of about 57,600 m3 /d (Mitiche, 2010)

5.1 Assessment of Seawater Desalination Facilities in Algeria

Desalination plays a crucial role in Algeria's strategy to address water scarcity, especially along the coastal regions. This section provides an updated overview of the country's operational desalination plants, focusing on their technical specifications, capacity, location, and efficiency. The information presented is essential for evaluating the current infrastructure and guiding future improvements in water resource management.

Tableau 6: Technical and Operational Profile of Most Algerian Desalination Plants (GWI, 2024)

No.	Plant Name	Location	Capacity (m^3/day)	Technology	Start-Up Year
1	Hamma	Algiers	200,000	Reverse Osmosis	2008
2	Beni Saf	Aïn Témouchent	200,000	Reverse Osmosis	2010
3	Kahrama	Arzew	125,000	Reverse Osmosis	2005
4	Fouka	Tipaza	120,000	Reverse Osmosis	2010
5	Cap Djinet	Boumerdès	100,000	Reverse Osmosis	2008
6	Skikda	Skikda	100,000	Reverse	2009

				Osmosis	
7	Mostaganem	Mostaganem	200,000	Reverse Osmosis	2010
8	El Mactaa	Oran	500,000	Reverse Osmosis	2016
9	Chatt El Hilal	El Tarf	100,000	Reverse Osmosis	2022
10	Tipaza	Tipaza	100,000	Reverse Osmosis	2022
11	Béjaïa	Béjaïa	50,000	Reverse Osmosis	2022
12	Cap Blanc	Oran (Aïn El Kerma)	300,000	Reverse Osmosis	2025
13	Souk El Tenine	Boumerdès	50,000	Reverse Osmosis	2023
14	Zéralda	Algiers	50,000	Reverse Osmosis	2023
15	Bou Ismaïl	Tipaza	50,000	Reverse Osmosis	2023
16	El Tarf (extension)	El Tarf	300,000	Reverse Osmosis	2023
17	Ténès	Chlef	100,000	Reverse Osmosis	2022
18	Béni Haoua	Chlef	100,000	Reverse Osmosis	2022

19	El Marsa	Skikda	50,000	Reverse Osmosis	2022
20	Marsat El Hadjadj	Oran	100,000	Reverse Osmosis	2022
21	Djen Djen	Jijel	100,000	Reverse Osmosis	2023
23	Tarf (pilot plant)	El Tarf	10,000	Reverse Osmosis	2015
24	Ghazaouet	Tlemcen	100,000	Reverse Osmosis	2022
25	Dellys	Boumerdès	50,000	Reverse Osmosis	2023
26	Cherchell	Tipaza	100,000	Reverse Osmosis	2023

5.1 Government Policies and Strategies Regarding Water Scarcity

The Algerian government has taken significant steps to address the critical issue of water scarcity, which has emerged as a serious challenge due to the country's predominantly arid climate and increasing population demands. Recognizing the urgency of this situation, the government established its National Water Strategy (NWS) in the 2000s, which outlines a comprehensive approach to water resource management, with a strong emphasis on desalination as a key solution.

Desalination facilities are being developed along Algeria’s Mediterranean coast, where the majority of the population lives. This technological investment allows for the conversion of seawater into potable water, helping to mitigate shortages and ensure a more reliable water supply. These facilities not only enhance the availability of drinking water but also play a crucial role in reducing dependency on dwindling freshwater sources such as rivers and aquifers.

To complement desalination efforts, the Algerian government is actively promoting water conservation practices across various sectors. Public awareness campaigns aim to educate citizens about the importance of water conservation, particularly in agricultural practices, which represent a significant portion of the country’s water consumption. By advocating for more efficient irrigation techniques and selecting drought-resistant crops, the government is encouraging farmers to use water more judiciously and sustainably.

In addition to conservation, improved management of existing water resources is essential to the country’s overall strategy. This includes upgrading water distribution systems to prevent leaks and reduce water losses, implementing better monitoring practices, and enhancing maintenance efforts to ensure that infrastructure operates optimally. Such measures aim to maximize the efficiency of the water that is already available.

The use of treated wastewater for non-potable applications represents another innovative solution in Algeria’s approach to water management. By treating wastewater for agricultural irrigation, industrial processes, and other uses, the government can conserve freshwater supplies for drinking and essential needs. This practice not only contributes to sustainable water use but also supports agricultural productivity, thereby benefiting the economy.

Integrating desalinated water into the broader national supply system is also a fundamental principle of the NWS. This strategy involves blending desalinated water with other sources to create a more diversified and resilient water supply network. By reducing reliance on depleted groundwater resources, Algeria aims to secure a sustainable water future.

Overall, the Algerian government's multi-faceted approach to water scarcity—combining infrastructure development, conservation efforts, resource management, and innovative reuse strategies—is designed to build a resilient water supply system. These initiatives are crucial in meeting the growing demands of the population while safeguarding the environment, ensuring that future generations will have access to sufficient and safe water resources. Through these comprehensive efforts, Algeria is working towards a more sustainable and secure water future that addresses both current challenges and long-term sustainability.

5.2 Environmental Economic Factors Influencing Desalination Initiatives in Algeria

Desalination plants in Algeria are facing increasing challenges due to climate change. Most of these plants are located along the northern coasts of the country, areas directly exposed to extreme climatic events such as rising sea levels, higher temperatures, and changing rainfall patterns (Cambridge, 2022)

One of the main impacts is the increase in seawater temperatures, which leads to reduced efficiency of desalination plants, especially those relying on Reverse Osmosis (RO) technology. Higher water temperatures increase the energy required for the desalination process and reduce the lifespan of membranes used in the system.

Additionally, rising sea levels pose a threat to the coastal infrastructure of the plants, necessitating additional investments to strengthen protections against flooding and coastal storms. Moreover, changes in seawater salinity due to decreased precipitation and increased evaporation can affect plant performance, as higher salinity levels require more energy for desalination, thus increasing operational and maintenance.

Figure 16 : Damaged membrane due to high salinity (BWC, 2025)

Strong storms and extreme weather fluctuations also lead to higher concentrations of sediments and impurities in the intake water, which imposes extra challenges on pre-treatment systems and accelerates the corrosion of equipment.

Chapter 2

Cutting-Edge Innovations in Geographic Information Systems (GIS)

1 Spatial analysis and GIS in Desalination Studies

Geographic Information Systems (GIS) have evolved into powerful tools for spatial data management, analysis, and visualization across a wide range of disciplines, including urban planning, environmental monitoring, and water resource management. GIS integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information

Recent advancements in GIS technology have significantly enhanced its capabilities. These include the integration of real-time data through remote sensing and IoT, cloud-based GIS platforms (such as ArcGIS Online and Google Earth Engine), and the use of artificial intelligence for predictive spatial analysis (Esri, 2023 – website). Modern GIS tools support 3D modeling, spatial-temporal analysis, and web mapping, enabling more interactive and detailed geospatial studies.

In the context of water resource management and desalination, GIS has become indispensable. It allows researchers and decision-makers to:

- Identify suitable sites for infrastructure development,
- Monitor coastal environmental conditions,
- Evaluate spatial criteria for sustainability assessments,
- Support multi-criteria decision-making processes by integrating diverse data layers

1.1 Overview of Spatial Assessment Tools

Spatial assessment tools are essential for analyzing spatial data and making informed decisions about geographic regions. These tools use geographic information systems (GIS), remote sensing, statistical models, and visualization techniques to process, analyze, and display spatial information. These tools play a crucial role in urban planning, environmental management, resource allocation, disaster risk management, and more.

1.2 Types of Spatial Assessment Tools:

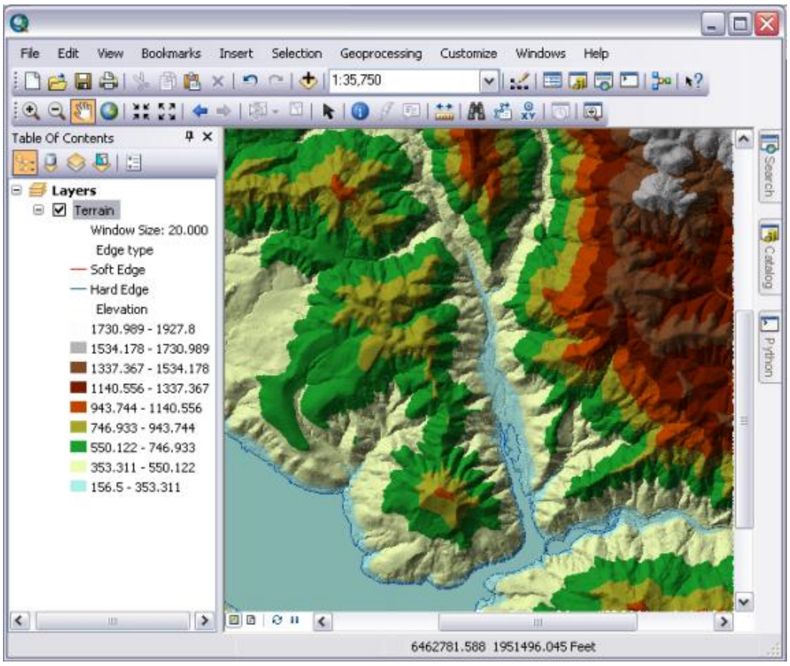
1.2.1 GIS Software

GIS software enables users to manage, analyze, and visualize spatial data. These tools allow users to interact with geographic information and derive meaningful insights for decision-making.

ArcGIS:

ArcGIS is a commercial GIS platform developed by Esri, providing a suite of tools for mapping, spatial analysis, geoprocessing, and data management. It is widely used in industries such as urban planning, transportation, and environmental management. Key tools include Spatial Analyst, Network Analyst, and 3D Analyst, which are used for analyzing spatial patterns and trends.

Application: Used for zoning, land-use planning, environmental impact assessments, and urban development.



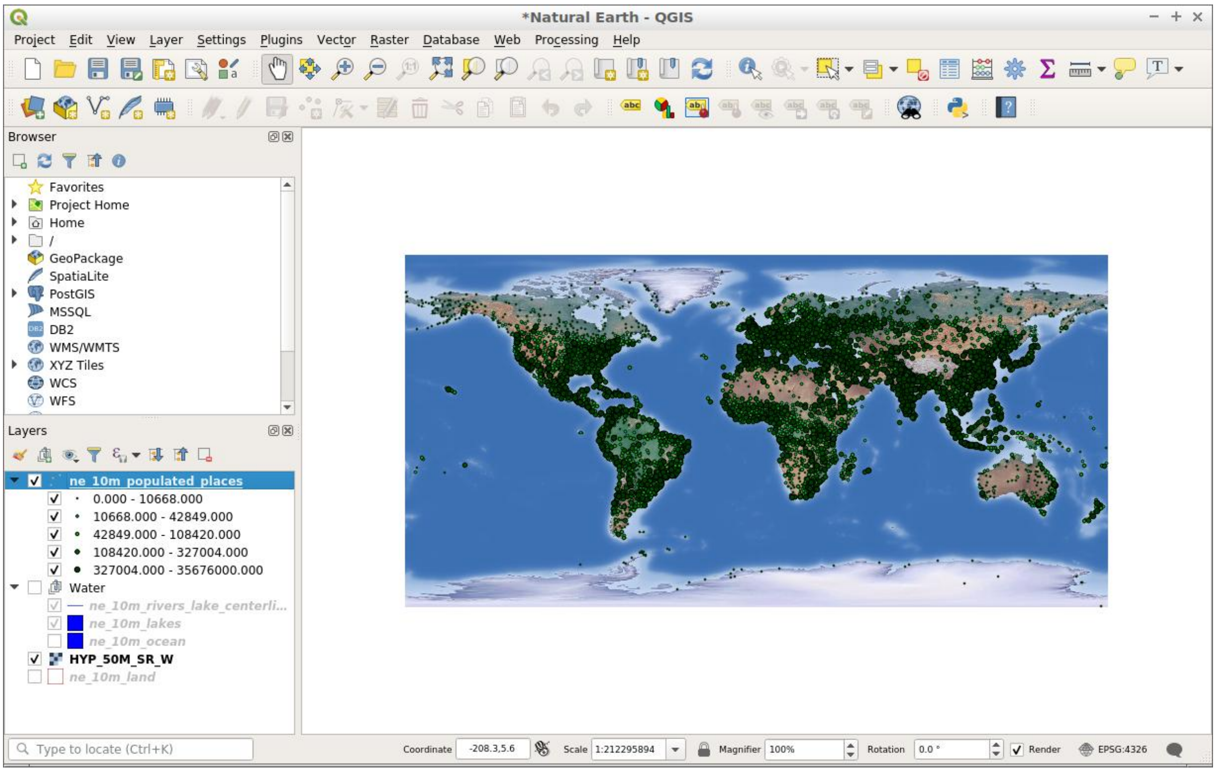
Window Size: 20.000

Figure 17 : ArcGIS Pro Interface Displaying Terrain Layer Classification and Symbology

QGIS:

QGIS is an open-source GIS platform that is highly customizable, offering a wide variety of plugins for spatial analysis, geospatial data manipulation, and visualization. It is favored for its flexibility, cost-effectiveness, and strong user community support.

Application: Used in academia, government projects, and small-scale enterprises that require spatial analysis and data visualization.



Coordinate -208.3,5.6
Scale 1:212295894
Magnifier 100%
Rotation 0.0 °

Figure 18: QGIS Interface Showing Natural Earth Dataset with Population and Water Layers

1.2.2 Remote Sensing

Remote sensing tools collect data from satellite imagery or airborne sensors to monitor and assess environmental and geographical changes. These tools allow for large-scale, real-time monitoring of land, water, and atmospheric changes.

Google Earth Engine: Google Earth Engine is a robust cloud-based platform for processing satellite imagery and other geospatial data. It enables environmental monitoring, deforestation analysis, and other time-series analyses by utilizing a vast repository of historical satellite imagery.

Application: Monitoring deforestation, agricultural land use, and urban sprawl.

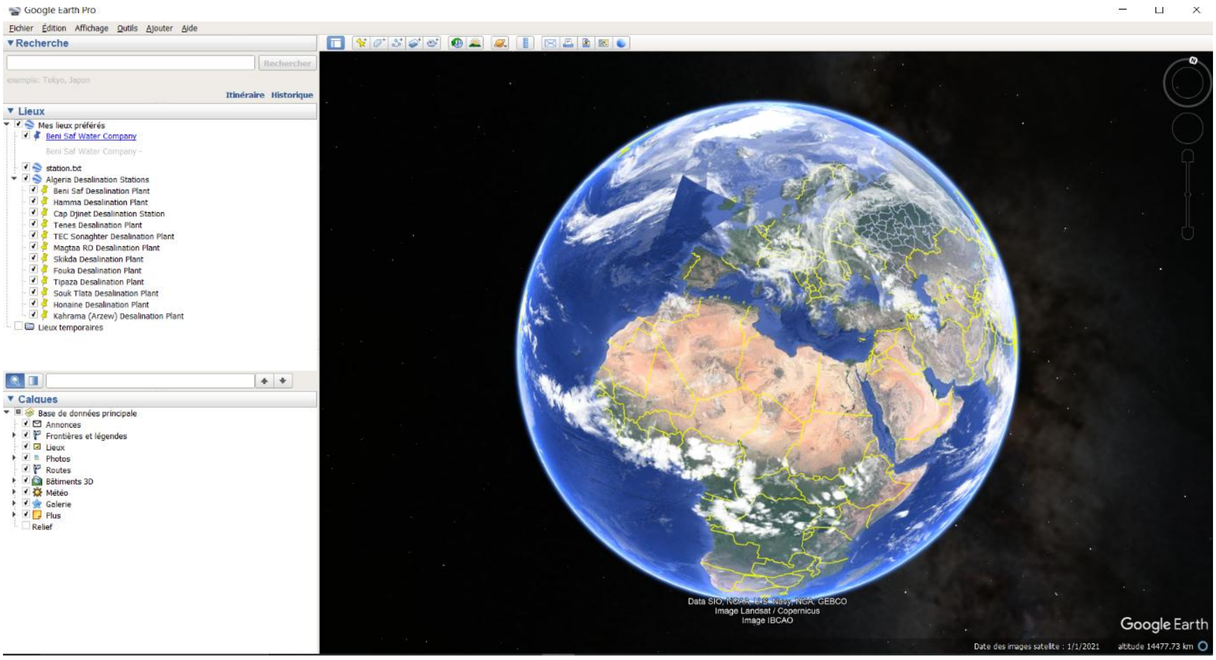
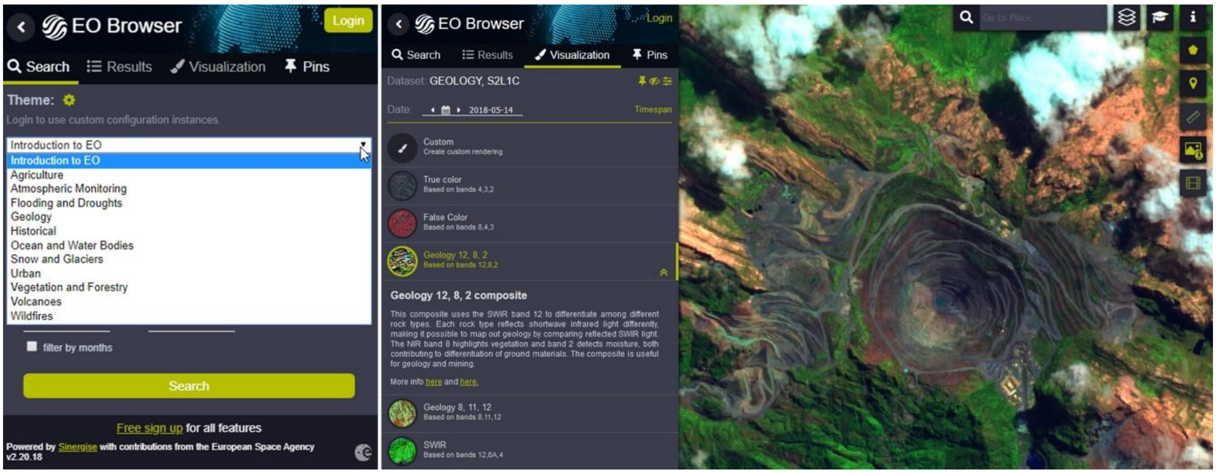


Figure 19: Google Earth Pro Interface

Sentinel Hub: Sentinel Hub is another platform that utilizes data from the Sentinel satellites to provide a wide range of environmental analysis and monitoring capabilities. It supports satellite image processing, which can be used for land cover mapping, agriculture monitoring, and climate change assessment.

Application: Tracking changes in vegetation, water bodies, and urban areas over time.



Theme: Introduction to EO

Login to use custom configuration instances.

☐ filter by months

Free sign up for all features

Powered by Sinergise with contributions from the European Space Agency
v2.20.18

Dataset: GEOLOGY, S2L1C

Date: 2018-05-14

Geology 12, 8, 2 composite

This composite uses the SWIR band 12 to differentiate among different rock types. Each rock type reflects shortwave infrared light differently, making it possible to map out geology by comparing reflected SWIR light. The NIR band 8 highlights vegetation and band 2 detects moisture, both contributing to differentiation of ground materials. The composite is useful for geology and mining.

More info here and here.

Figure 20: EO Browser Interface Displaying Geological Composite Imagery Analysis

1.2.3 Spatial Statistical Analysis

Spatial statistics involves using statistical methods to analyze spatial data and identify patterns or relationships that are geographically correlated. These tools are critical in detecting trends, clusters, and outliers in spatial datasets.

GeoDa:

GeoDa is an open-source software tool for spatial data analysis, offering advanced spatial statistical functions such as spatial autocorrelation**,** spatial regression, and hotspot analysis. It is instrumental in urban planning and environmental studies to identify spatial patterns and inequalities.

Application: Analyzing the spread of diseases, crime hotspots, or urban development patterns.

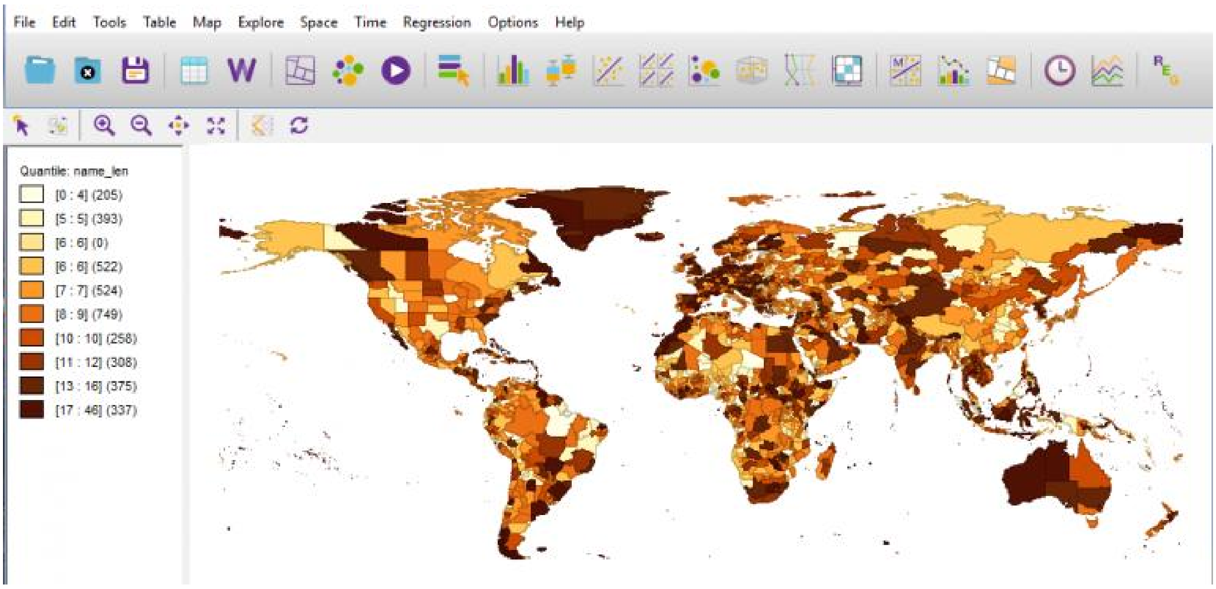


Figure 21:GeoDa Thematic Mapping Interface for Spatial Data Visualization

SPSS and R (Spatial Packages):

Tools like SPSS and the R programming language provide specific spatial statistical packages that allow users to perform complex spatial analysis, such as Kriging, Voronoi tessellation, and spatial interpolation.

Application: Used in environmental studies, epidemiology, and social science research for spatial data analysis.

1.2.4 3D Visualization Tools

3D visualization tools enable the modeling, simulation, and visualization of geographical features and urban developments in three dimensions. These tools enable planners and decision-makers to better understand spatial interactions and scenarios.

City Engine:

City Engine is a 3D modeling software for urban planning and architectural design. It enables users to create detailed 3D models of cities and assess the impact of various urban designs on the environment and society.

Application: Used for visualizing and simulating urban growth, planning public spaces, and sustainably designing cities.

SketchUp:

SketchUp is a 3D modeling tool used for architectural design, landscape architecture, and urban planning. It offers intuitive tools for building detailed, realistic 3D models that help visualize building structures, roads, and other spatial features.

Application: Popular in architecture and landscape design for visualizing buildings and urban plans.

1.2.5 Suitability Analysis

Suitability analysis helps in evaluating the best locations for specific activities, such as urban development, agriculture, or infrastructure projects, based on spatial data and criteria.

Raster-based Analysis:

This type of analysis uses raster data layers to represent different environmental, economic, and social factors such as land slope, proximity to resources, and infrastructure. By overlaying these factors, users can identify the most suitable locations for specific activities.

Application: Identifying suitable sites for renewable energy plants, residential zoning, or agricultural cultivation.

Hydrological assessment tools are used to model and simulate water systems, including river basins, watersheds, and floodplains, helping decision-makers manage water resources and reduce flood risks.

HEC-RAS:

Developed by the US Army Corps of Engineers, HEC-RAS is software for simulating water flow, floodplain analysis, and sediment transport in rivers and streams. It is widely used for flood risk management and hydrological studies.

Application: Flood modeling, river management, and infrastructure design to minimize flood damage.

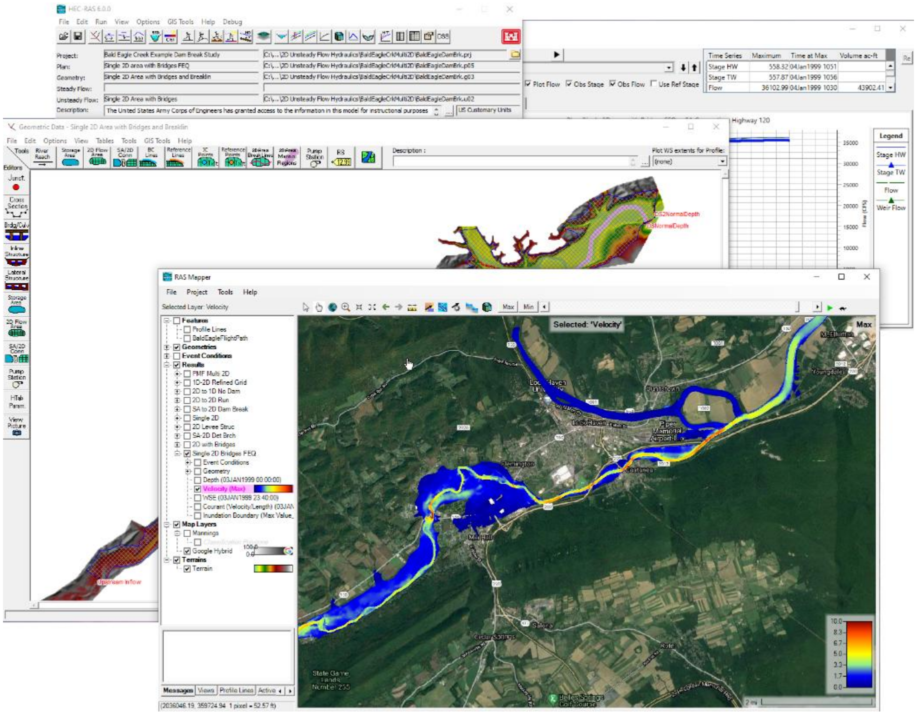


Figure 22 :HEC-RAS: Free Software for River Modeling and Flood Risk Analysis with GIS Integration

SWAT (Soil and Water Assessment Tool):

SWAT is a hydrological model used to simulate the movement of water, sediment, and pollutants across landscapes. It helps in assessing the impacts of land use changes, climate, and agricultural practices on water quality.

Application: Water resource management, agricultural impact assessments, and watershed management.

1.2.6 Multi-Criteria Decision Analysis (MCDA)

Multi-Criteria Decision Analysis (MCDA) is a set of techniques or methods used to evaluate and make decisions when multiple, often conflicting, criteria are involved. It is particularly useful in complex decision-making scenarios such as environmental planning, resource management, and infrastructure development, like the assessment of seawater desalination plants.

1.2.6.1 Definition and Purpose

MCDA helps decision-makers systematically compare various alternatives based on multiple qualitative and quantitative criteria. The primary goal is to identify the most suitable option or to rank the alternatives based on a predetermined set of criteria and stakeholder preferences.

1.2.6.2 Common Steps in MCDA

1. **Problem Definition**

   Clearly define the objective of the decision-making process (selecting the best location for a desalination plant).

2. **Identification of Alternatives**

   List all possible alternatives (different desalination plants along the Algerian coast).

3. **Criteria Selection**

   Choose relevant criteria for evaluation (water production capacity, environmental impact, cost, proximity to population centers, etc.).

4. **Weight Assignment**

   Assign weights to each criterion based on its importance using expert judgment or stakeholder input.

5. **Performance Evaluation**

   Score each alternative against each criterion.

6. **Application of the MCDA Method**

   Use an MCDA method, such as TOPSIS, AHP, or ELECTRE, to calculate scores or ranks for each alternative.

7. **Analysis and Decision-Making**

   Interpret results and make informed decisions.

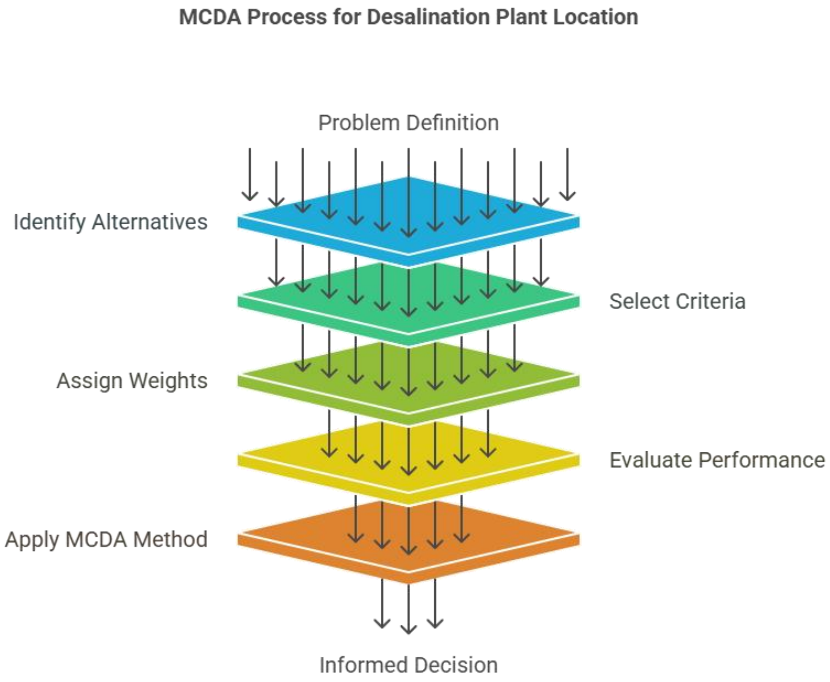


Figure 23/ MCDA STEPS

1.2.6.3 Types of MCDA Methods

- TOPSIS (Technique for Order Preference by Similarity to Ideal Solution)

  Evaluates alternatives based on their distance to an ideal and anti-ideal solution.

- AHP (Analytic Hierarchy Process)

  Breaks down the decision problem into a hierarchy and uses pairwise comparisons to assign weights.

- ELECTRE (Elimination and Choice Expressing Reality)

  Uses outranking to compare alternatives based on thresholds.

- PROMETHEE (Preference Ranking Organization Methods for Enrichment Evaluations)

  Provides ranking based on preference flows between alternatives.

1.2.6.4 Applications in Desalination and Water Resource Management

MCDA is widely used to:

- Select optimal sites for seawater desalination plants
- Assess the sustainability of water treatment options
- Evaluate the environmental and socio-economic impact of water infrastructure projects
- Prioritize investment and maintenance plane

In this study, we apply MCDA to evaluate and rank existing seawater desalination plants along the Algerian coast. This approach enables us to compare multiple plants based on a set of weighted criteria, including water quality, environmental impact, infrastructure availability, plant age, and the integration of renewable energy, among others. By assigning different weights to these criteria, we can simulate various decision-making perspectives and policy priorities.

A crucial strength of MCDA lies in its capability to perform sensitivity analyses. By adjusting the weights of the criteria, we can observe how rankings change and thereby identify which factors have the greatest influence on plant performance. This process not only helps us determine the best-performing plants but also reveals underlying problems or inefficiencies in lower-ranked facilities. For example, if a plant's ranking significantly drops when environmental impact is given higher weight, it may indicate a need for more sustainable practices at that site. Thus, MCDA does not merely rank options, it also provides a diagnostic tool for understanding and addressing critical issues in desalination plant management.

1.2.6.5 Advantages and Limitations

Advantages :

- Handles complex decisions with multiple criteria
- Incorporates both qualitative and quantitative data
- Provides transparency and structured reasoning

Limitations :

- Subjectivity in weighting criteria
- Sensitive to data quality and normalization methods
- May require expert input and stakeholder consensus

1.3 Application of Spatial Analysis to Infrastructure Planning

Spatial analysis is a powerful tool in infrastructure planning, enabling the optimization of design, placement, and management of physical infrastructure systems, such as roads, utilities, and public services. By integrating geographic data with advanced analytical techniques, spatial analysis enables planners and engineers to make data-driven decisions that enhance the efficiency, sustainability, and resilience of infrastructure projects. Below, we will explore various real-world applications of spatial analysis in infrastructure planning.

1.3.1 Site Selection and Optimal Routing

Explanation: Spatial analysis helps determine the most suitable locations for new infrastructure projects and optimize routes for networks such as transportation and utilities. By evaluating various factors, including land use, proximity to resources, environmental concerns, and existing infrastructure, spatial analysis ensures that the best possible decisions are made to minimize costs and maximize benefits.

Example: For the Trans-Alaska Pipeline, spatial analysis played a crucial role in selecting the optimal route that avoided environmentally sensitive areas, minimized construction costs, and ensured operational efficiency. GIS was used to analyze topography, wildlife habitats, and proximity to existing infrastructure to design the most effective and least disruptive route.

Figure 24 : ALASKA PIPE LINE (State of Alaska Geoportal, 2025)

1.3.2 Land Use and Zoning

Explanation: Spatial analysis is key to managing land use and ensuring that infrastructure development aligns with zoning regulations. By examining factors such as population density, current land use, and future growth projections, spatial analysis enables planners to make informed decisions about where to locate infrastructure to support sustainable urban development.

Example: In New York City, spatial analysis played a vital role in the Comprehensive Waterfront Plan, helping to determine where new infrastructure should be developed along the waterfront. By analyzing land-use data, environmental factors, and the needs of the growing population, the plan created new spaces for both commercial development and public parks while maintaining ecological balance.

Figure 25 : The boundaries of the New York City Waterfront Revitalization Program (arcgis, 2025)

1.3.3 Environnemental Impact Assessment (EIA)

Explanation: Before building new infrastructure, spatial analysis with GIS helps assess environmental impacts, guiding planners to reduce harm to nature and communities.

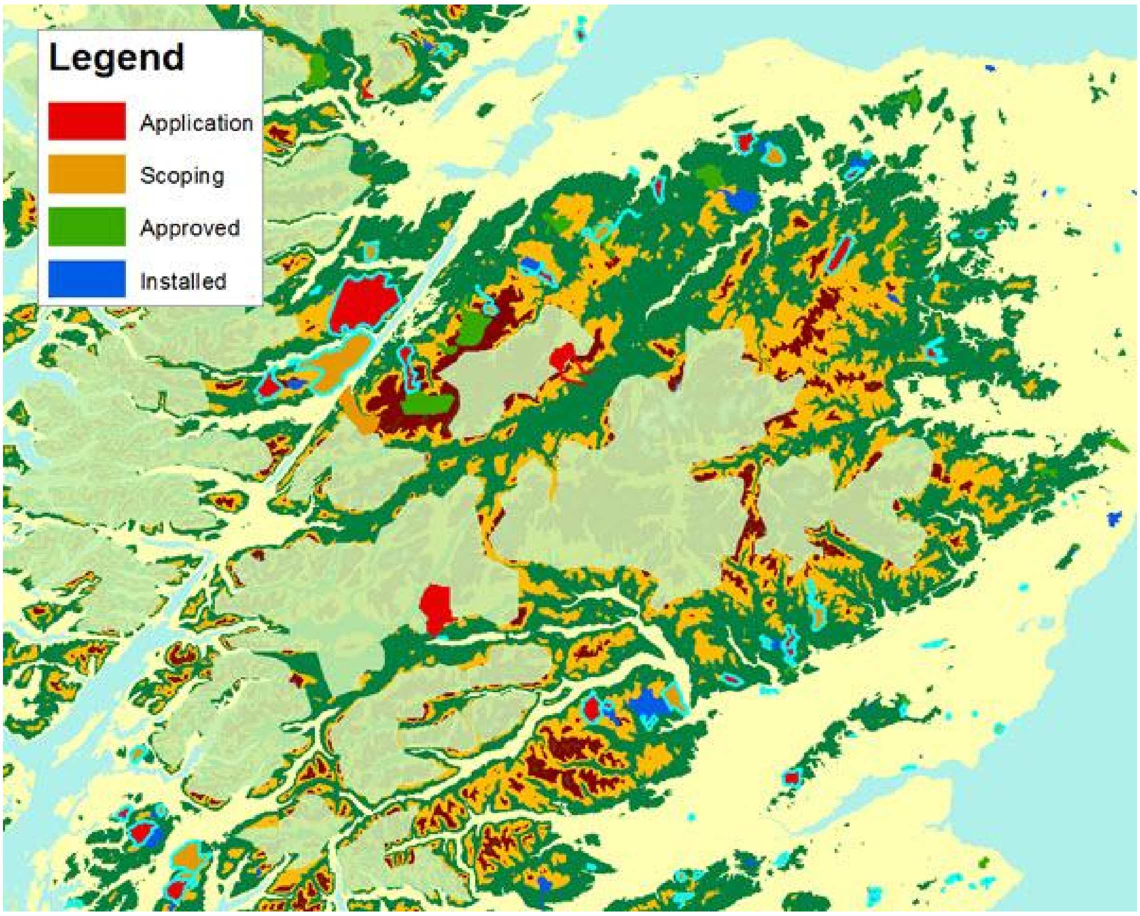


Figure 26 : Wind Farm in Northern Scotland (arcgis, 2025)

1.3.4 Traffic Flow and Transport Networks

Explanation: Spatial analysis is essential for optimizing traffic flow and improving transportation networks. By analyzing data on road conditions, traffic patterns, population growth, and transportation demands, planners can design systems that reduce congestion, improve accessibility, and enhance overall mobility.

Example: The London Congestion Charge Zone is a prime example of spatial analysis in action. By mapping traffic patterns and congestion points, spatial analysis enabled the design of a congestion charge system that reduced traffic in the city center, improved air quality, and encouraged the use of public transportation.

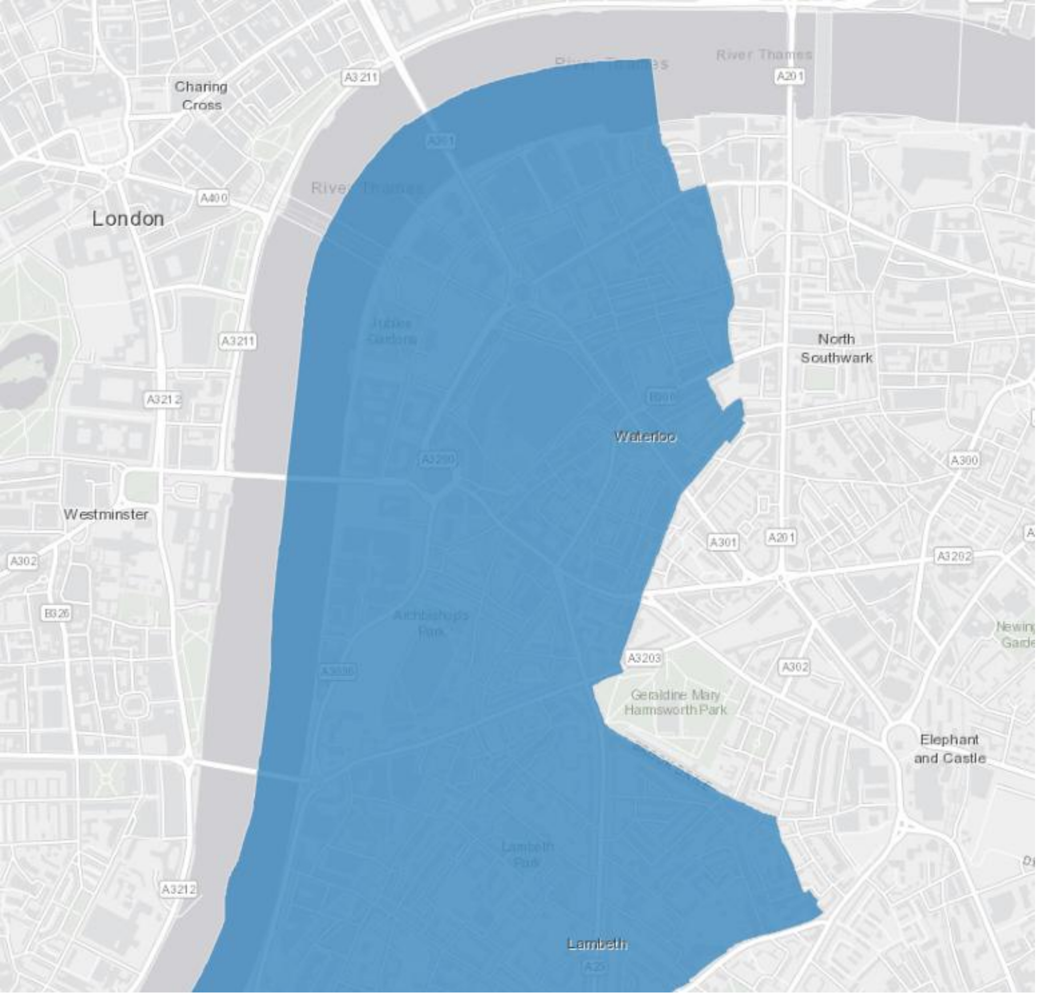


Figure 27: London Congestion Charge Zone (arcgis, 2025)

1.3.5 Utilities and Services Distribution

Explanation: Spatial analysis helps optimize the distribution of utilities such as water, electricity, and waste management. By considering factors such as population density, land use, and existing infrastructure, spatial analysis enables the efficient allocation of resources, ensuring that services reach all areas in need.

Example: In Los Angeles, spatial analysis was used to optimize the city's water distribution system. GIS tools allowed the city to identify areas with insufficient water supply, prioritize infrastructure upgrades, and allocate resources more effectively to meet the demands of a growing population.

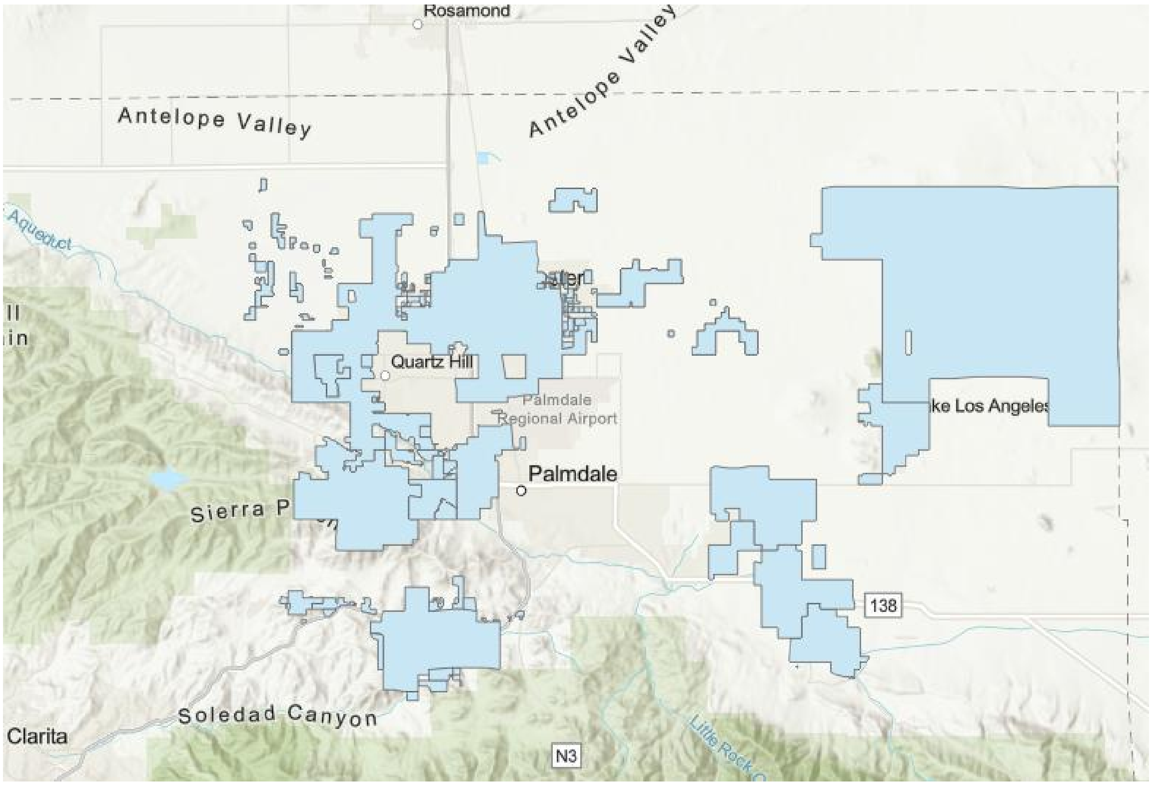


Figure 28 : Los Angeles spatial analysis (Zrelli, 2025)

1.3.6 Risk Assessment and Disaster Preparedness

Explanation: Infrastructure planning must account for natural hazards such as earthquakes, floods, and storms. Spatial analysis helps identify high-risk areas, ensuring that infrastructure is designed to withstand such events. It also aids in planning emergency routes, disaster response systems, and evacuation plans to protect communities during natural disasters.

Example: After the 2011 Tohoku Earthquake in Jap**an**, GIS was used to assess the impact on infrastructure and predict future risks. Spatial analysis helped identify vulnerable areas and inform the design of more resilient infrastructure, as well as improve evacuation routes and disaster management protocols.

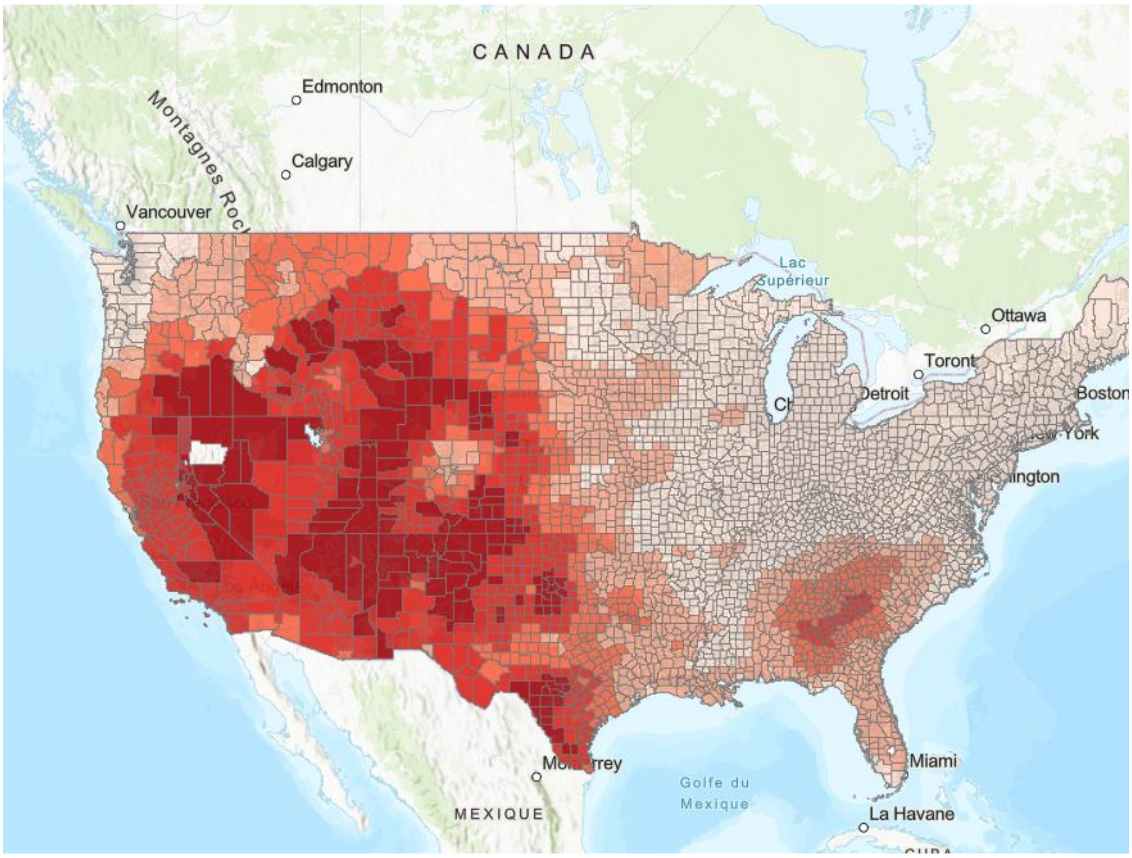


Figure 29 : Us national risk index (arcgis, 2025)

Chapter 3

Compilation and Presentation of Empirical Data

1 Global Mapper: A Comprehensive GIS Platform for Spatial Analysis

Global Mapper is a professional yet user-friendly Geographic Information System (GIS) software developed by Blue Marble Geographics. Since its first release in the late 1990s, Global Mapper has evolved into one of the most versatile and accessible GIS tools available, widely used in sectors such as environmental science, engineering, hydrology, geology, urban planning, and defense.

Unlike more complex platforms such as ArcGIS or QGIS, Global Mapper combines powerful geospatial processing capabilities with a relatively low learning curve, making it an excellent choice for applied field research where both technical performance and ease of use are crucial. In this study, Global Mapper plays a central role in managing spatial datasets, performing terrain analysis, assessing environmental impacts, and producing cartographic outputs relevant to the positioning and evaluation of desalination plants in the Algerian Bay.

2 Results and Discussion

2.1 Spatial Distribution of Existing Desalination Plants

2.1.1 Data Collection :

As an initial step in our research, we conducted field visits to the nearest seawater desalination plants located in the western region of Algeria. These included the Beni Saf Water Company facility, the Souk Tlata desalination plant Tlemcen, and the Cap Blanc desalination station Oran. The primary objective of these visits was to collect accurate and site-specific data essential for our spatial and technical assessment of desalination infrastructure.

During these visits, particular attention was given to several key parameters. First and foremost, we recorded the exact geographical location of each plant, along with the total surface area occupied by the facilities, measured in hectares. This information is critical for understanding the spatial footprint and potential environmental impact of each site. Furthermore, we gathered detailed data on the daily water production capacity of each plant, which provides insight into their operational performance and their ability to meet regional water demands.

In addition to production metrics, we also documented the energy consumption rates associated with the desalination processes at each station. This included identifying the type and quantity of energy used per cubic meter of desalinated water, which is vital for evaluating the overall efficiency and sustainability of the plants. Other observed indicators included technological processes in use, operational constraints, and any integration with renewable energy sources if applicable.

These preliminary site visits and data collection activities formed the foundation for our subsequent analytical work, allowing for a more comprehensive evaluation of desalination plant performance across multiple criteria.

2.1.1.1.1 Beni Saf Seawater Desalination Plant:

- Coordinates : from :35.360666162, -1.26471388889 (Beni Saf Water Company)
- Producing Capacity: 200,000 m³/day
- Alimentation Area: Wilaya of Aïn Témouchent and parts of Oran (approximately 950,000 inhabitants covered)
- Energy Consumption: 4.15 kWh/m³
- Technology Used: Reverse Osmosis (RO) with pre-filtration, sand & anthracite filters, cartridge filters, chemical pre-treatment (sodium hypochlorite, ferric chloride, sulfuric acid, sodium metabisulfite, dispersant)

• Workers Number: 64 employees

• Capital Cost (DZD): Approx. 240 million USD (~36 billion DZD, assuming 1 USD ≈ 150 DZD)

• Water Quality: High, meets WHO standards

• Availability to Infrastructure: Excellent; connected to regional water supply networks serving Oran and Ain Témouchent

• Plant Age (Years): 13 years

• Construction Year: March 2010 (commissioned and operational)

• Renewable Energy Integration: Energy recovery system with isobaric chambers (ERI) at 95% efficiency; no solar/wind integration reported

• Site Position (Strategic/Proximity): Coastal, at Chatt El Hillal near Beni Saf; strategically positioned to supply water for domestic use and agriculture

• Pump Performance Efficiency (%): Not specified explicitly, but energy recovery system efficiency at 95%

• RO Treatment Performance (%): Not specified explicitly; RO is known for >95% salt rejection

• Additional Notes:

- Seawater intake through submarine outfall
- Post-treatment with calcium carbonate and sodium hypochlorite
- Station consists of 10 desalination units
- Supports agricultural irrigation indirectly by freeing surface water resources and supporting wastewater treatment for irrigation (13 million m³ reclaimed water used for 1,300 ha agricultural land)

2.1.1.1.2 Kahrama desalination plant:

Coordinates : from :35.807585, -0.246879

- Producing Capacity : Approximately 100,000 m^3/day
- Alimentation Area : Wilaya of Mostaganem and surrounding areas
- Energy Consumption : Approx. 3.9–4.1 kWh/m^3
- Technology Used : Reverse Osmosis (RO) with standard pre-treatment filters
- Workers Number : Around 70 employees
- Capital Cost (DZD) : Estimated around 15 billion DZD
- Water Quality : Meets national and WHO standards
- Availability to Infrastructure : Good; connected to regional water distribution and power grids
- Plant Age (Years) : About 10 years
- Construction Year : 2013
- Renewable Energy Integration : None reported; fully grid-powered
- Site Position (Strategic/Proximity) : Coastal site near Mostaganem; strategically placed to serve the local population and industrial zones
- Pump Performance Efficiency (%) : Estimated 80–85%
- RO Treatment Performance (%) : ~97% salt rejection rate; stable operation under standard conditions

2.1.1.1.3 Fouka 1

- Coordinates: 36.678558, 2.763978
- Producing Capacity: 120,000 m^3/day
- Alimentation Area: Tipaza Province
- Technology Used: Reverse Osmosis (RO) with pre-treatment
- Water Quality: Meets national standards

- Availability to Infrastructure: Good; connected to local water and electricity grids
- Plant Age (Years): Approx. 13 years
- Construction Year: 2011
- Site Position (Strategic/Proximity): Coastal, near Tipaza; serves regional demand

2.1.1.1.4 Fouka 2

- Coordinates: 36.676127, 2.756833
- Producing Capacity: 300,000 m³/day
- Alimentation Area: Provinces of Algiers, Tipaza, and Blida
- Technology Used: Reverse Osmosis (RO) with pre-treatment
- Capital Cost (DZD): Estimated around 58 billion DZD
- Water Quality: Meets national standards
- Availability to Infrastructure: Excellent; integrated into national supply network
- Plant Age (Years): Around 1 year
- Construction Year: 2025
- Site Position (Strategic/Proximity): Coastal, strategically located to supply major regions

2.1.1.1.5 Cap Djinet

- Coordinates: 36.838651, 3.692668
- Producing Capacity: 100,000 m³/day
- Alimentation Area: Boumerdès and eastern Algiers suburbs
- Technology Used: Reverse Osmosis (RO) with pre-treatment
- Water Quality: Meets WHO standards
- Availability to Infrastructure: Excellent; connected to national water and power networks
- Plant Age (Years): Approx. 12 years
- Construction Year: 2012

- Site Position (Strategic/Proximity): Coastal, near Cap Djinet port and urban zones

2.1.1.1.6 Skikda

- Coordinates: 36.882956, 6.965998
- Producing Capacity: 100,000 m³/day
- Alimentation Area: Skikda city and surrounding communes
- Technology Used: Reverse Osmosis (RO)
- Water Quality: Meets national drinking water standards
- Availability to Infrastructure: Excellent; integrated into local distribution and energy systems
- Plant Age (Years): Approx. 14 years
- Construction Year: 2011
- Site Position (Strategic/Proximity): Coastal, adjacent to Skikda industrial and residential zones

2.1.1.1.7 Mostaganem

- Coordinates: 36.014374, 0.128273
- Producing Capacity: 200,000 m³/day
- Alimentation Area: Mostaganem and surrounding regions
- Energy Consumption: Approx. 3 kWh/m³
- Technology Used: Reverse Osmosis (RO)
- Capital Cost (DZD): Estimated around 240 million USD
- Water Quality: Meets WHO standards
- Availability to Infrastructure: Connected to national electricity grid and water distribution networks
- Plant Age (Years): Approx. 12 years
- Construction Year: 2012

- Renewable Energy Integration: None
- Site Position (Strategic/Proximity): Near Oran, strategic regional water supply location
- RO Treatment Performance (%): ~98% salt rejection rate

2.1.1.1.8 El Mactaa

- Coordinates: 35.786377, -0.149977
- Producing Capacity: 100,000 m³/day
- Alimentation Area: El Mactaa region and nearby communes
- Energy Consumption: Approx. 3.5 kWh/m³
- Technology Used: Reverse Osmosis (RO)
- Water Quality: Meets national standards
- Availability to Infrastructure: Connected to local electricity and water networks
- Plant Age (Years): Approx. 10 years
- Construction Year: 2014
- Renewable Energy Integration: None
- Site Position (Strategic/Proximity): Inland, serving agricultural and residential areas
- RO Treatment Performance (%): ~97% salt rejection rate

2.1.1.1.9 Tipaza

- Coordinates: 36.686876, 2.806797
- Producing Capacity: 150,000 m³/day
- Alimentation Area: Tipaza city and surrounding coastal areas
- Energy Consumption: Approx. 3.7 kWh/m³
- Technology Used: Reverse Osmosis (RO)
- Water Quality: Meets national drinking water standards
- Availability to Infrastructure: Excellent; integrated with local water and electricity networks
- Plant Age (Years): Approx. 9 years

- Construction Year: 2015
- Renewable Energy Integration: None
- Site Position (Strategic/Proximity): Coastal, near urban centers
- RO Treatment Performance (%): ~98% salt rejection rate

2.1.1.1.10 Béjaïa

- Coordinates: 36.847857, 4.923531
- Producing Capacity: 120,000 m³/day
- Alimentation Area: Béjaïa city and nearby communes
- Energy Consumption: Approx. 3.9 kWh/m³
- Technology Used: Reverse Osmosis (RO)
- Water Quality: Meets WHO and national standards
- Availability to Infrastructure: Good; connected to regional grids and water systems
- Plant Age (Years): Approx. 10 years
- Construction Year: 2014
- Renewable Energy Integration: None
- Site Position (Strategic/Proximity): Coastal, close to urban industrial zone
- RO Treatment Performance (%): ~97.5% salt rejection rate

2.1.1.1.11 Cap Blanc

- Coordinates: 35.685557, -0.983072
- Producing Capacity: 300,000 m³/day
- Alimentation Area: Wilayas of Oran, Aïn Témouchent, Mascara, Sidi Bel Abbès, Relizane
- Technology Used: Reverse Osmosis (RO)
- Workers Number: Around 1,500 during construction (by GCB and 5 subcontractors)
- Capital Cost (DZD): Approx. 2.4 billion USD
- Water Quality: Meets WHO standards

- Availability to Infrastructure: Excellent; includes 48 km of pipelines and two main reservoirs (50,000 m³ in Aïn Tassa and 30,000 m³ in Bousfer)
- Plant Age (Years): 1 year
- Construction Year: 2025
- Site Position (Strategic/Proximity): Coastal; near urban and industrial zones of Oran

2.1.1.1.12 Souk Tleta Desalination Plant (Wilaya de Tlemcen)

- Coordinates: 35.070239, -2.001117
- Producing Capacity: 200,000 m³/day (initial design capacity); currently operating at approximately 60,000 m³/day following rehabilitation efforts
- Alimentation Area: Tlemcen city and 19 surrounding communes
- Energy Consumption: Approx. 4.2 kWh/m³ (estimated)
- Technology Used: Reverse Osmosis (RO)
- Water Quality: Compliant with national and WHO drinking water standards
- Availability to Infrastructure: Good; connected to regional water and electricity networks
- Plant Age (Years): Approx. 14 years
- Construction Year: 2011
- Renewable Energy Integration: None
- Site Position (Strategic/Proximity): Coastal, serving both urban and rural populations
- Pump Performance Efficiency (%): Not specified
- RO Treatment Performance (%): ~96–97% salt rejection

2.1.1.1.13 Zéralda Desalination Plant

- Coordinates: 36.720752, 2.831249
- Producing Capacity: 10,000 m³/day
- Alimentation Area: Zéralda and western suburbs of Algiers

- Energy Consumption: Approx. 3.9 kWh/m³
- Technology Used: Reverse Osmosis (RO)
- Water Quality: Conforms to national potable water standards
- Availability to Infrastructure: Excellent; fully connected to urban water and electricity networks
- Plant Age (Years): Approx. 15 years
- Construction Year: 2010
- Renewable Energy Integration: None
- Site Position (Strategic/Proximity): Coastal, positioned near high-demand residential zones
- RO Treatment Performance (%): ~96% salt rejection rate

2.1.1.1.14 Bou Ismaïl Desalination Plant

- Coordinates: 36.656100, 2.706386
- Producing Capacity: 10,000 m³/day
- Alimentation Area: Bou Ismaïl and nearby towns in Tipaza Province
- Energy Consumption: Approx. 4.0 kWh/m³
- Technology Used: Reverse Osmosis (RO)
- Water Quality: Compliant with WHO drinking water standards
- Availability to Infrastructure: Good; linked to local distribution systems
- Plant Age (Years): Approx. 12 years
- Construction Year: 2012
- Renewable Energy Integration: None
- Site Position (Strategic/Proximity): Coastal, close to population centers
- RO Treatment Performance (%): ~96–97% salt rejection

2.1.1.1.15 Seawater desalination plant, Kedia Draouch, El Tarf

- Coordinates: 36.892520, 8.116516

- Producing Capacity: 50,000 m³/day
- Alimentation Area: El Tarf city and surrounding communes
- Energy Consumption: Approx. 4.1 kWh/m³
- Technology Used: Reverse Osmosis (RO)
- Water Quality: Meets national and WHO standards
- Availability to Infrastructure: Moderate; integrated into local grid and water system
- Plant Age (Years): Approx. 3 years
- Construction Year: 2022
- Renewable Energy Integration: None
- Site Position (Strategic/Proximity): Coastal, near the Tunisian border
- RO Treatment Performance (%): ~97% salt rejection

2.1.1.1.16 Ténès Desalination Plant

- Coordinates: 36.505842, 1.226392
- Producing Capacity: 50,000 m³/day
- Alimentation Area: Ténès city and surrounding coastal communities
- Energy Consumption: Approx. 4.2 kWh/m³
- Technology Used: Reverse Osmosis (RO)
- Water Quality: Conforms to WHO potable water standards
- Availability to Infrastructure: Good; connected to local networks
- Plant Age (Years): Approx. 2 years
- Construction Year: 2023
- Site Position (Strategic/Proximity): Coastal, serves growing population and tourism sector
- Pump Performance Efficiency (%):
- RO Treatment Performance (%): ~96.5% salt rejection

2.1.1.1.17 Béni Haoua Desalination Plant

- Coordinates: 36.540353, 1.569079
- Producing Capacity: 50,000 m³/day
- Alimentation Area: Béni Haoua and nearby communes in Chlef Province
- Energy Consumption: Approx. 4.1 kWh/m³
- Technology Used: Reverse Osmosis (RO)
- Water Quality: Meets Algerian and WHO drinking water standards
- Availability to Infrastructure: Good; integrated into regional water system
- Plant Age (Years): Approx. 2 years
- Construction Year: 2023
- Renewable Energy Integration: None
- Site Position (Strategic/Proximity): Coastal, positioned near rural and semi-urban zones
- Pump Performance Efficiency (%):
- RO Treatment Performance (%): ~96% salt rejection

2.1.1.1.18 El Marsa Desalination Plant (Wilaya of Skikda)

- Coordinates: 36.803942, 3.259191
- Producing Capacity: 70,000 m³/day
- Alimentation Area: El Marsa city and surrounding areas in Skikda Province
- Energy Consumption: Approx. 4.0 kWh/m³
- Technology Used: Reverse Osmosis (RO)
- Water Quality: Compliant with national drinking water standards
- Availability to Infrastructure: Good; connected to local water network and power grid
- Plant Age (Years): Approx. 4 years
- Construction Year: 2019
- Renewable Energy Integration: None

- Site Position (Strategic/Proximity): Coastal, serving industrial and residential zones
- RO Treatment Performance (%): ~97% salt rejection

2.1.1.1.19 Djen Djen Desalination Plant (Wilaya of Skikda)

- Coordinates: 36.883084, 6.966171
- Producing Capacity: 80,000 m³/day
- Alimentation Area: Skikda city and surrounding municipalities
- Energy Consumption: Approx. 4.0 kWh/m³
- Technology Used: Reverse Osmosis (RO)
- Water Quality: Compliant with national drinking water standards
- Availability to Infrastructure: Good; integrated with local water and power networks
- Plant Age (Years): Approx. 7 years
- Construction Year: 2016
- Renewable Energy Integration: None
- Site Position (Strategic/Proximity): Coastal, near Skikda industrial area
- RO Treatment Performance (%): ~97% salt rejection

2.1.1.1.20 Zéralda desalination plant

- Coordinates: 36.720768, 2.831296
- Producing Capacity: 100,000 m³/day
- Alimentation Area: Cherchell and neighboring communes in Tipaza
- Energy Consumption: Approx. 4.1 kWh/m³
- Technology Used: Reverse Osmosis (RO)
- Water Quality: Meets WHO and Algerian potable water standards
- Availability to Infrastructure: Excellent; integrated into local water and energy networks
- Plant Age (Years): Approx. 2 years
- Construction Year: 2023

• Renewable Energy Integration: None

• Site Position (Strategic/Proximity): Coastal, designed to support both urban consumption and tourism demand

• RO Treatment Performance (%): ~97% salt rejection

In our pursuit of building a comprehensive database on seawater desalination plants, we did not rely solely on theoretical sources. We went into the field, explored the plants firsthand, observed operational details, and broadened our understanding through dialogue with those who live the reality and possess the expertise. This collective effort is what gives our project its scientific credibility and practical value.

Data were gathered from multiple reliable sources:

- Official reports from the Ministry of Water Resources and Environment.
- Scientific articles and academic theses.
- Trusted websites of plant-operating companies.
- Satellite maps and imagery from Google Earth and Bing Maps.

These sources allowed for the compilation of general attributes such as production capacity, technology used, energy consumption, and service area.

2.1.2 Using Google Earth to Identify and Geolocate Plants

As some desalination plants were not precisely mapped in official sources, **Google Earth Pro** was used to locate them visually. The following steps were followed :

1. Open Google Earth Pro.

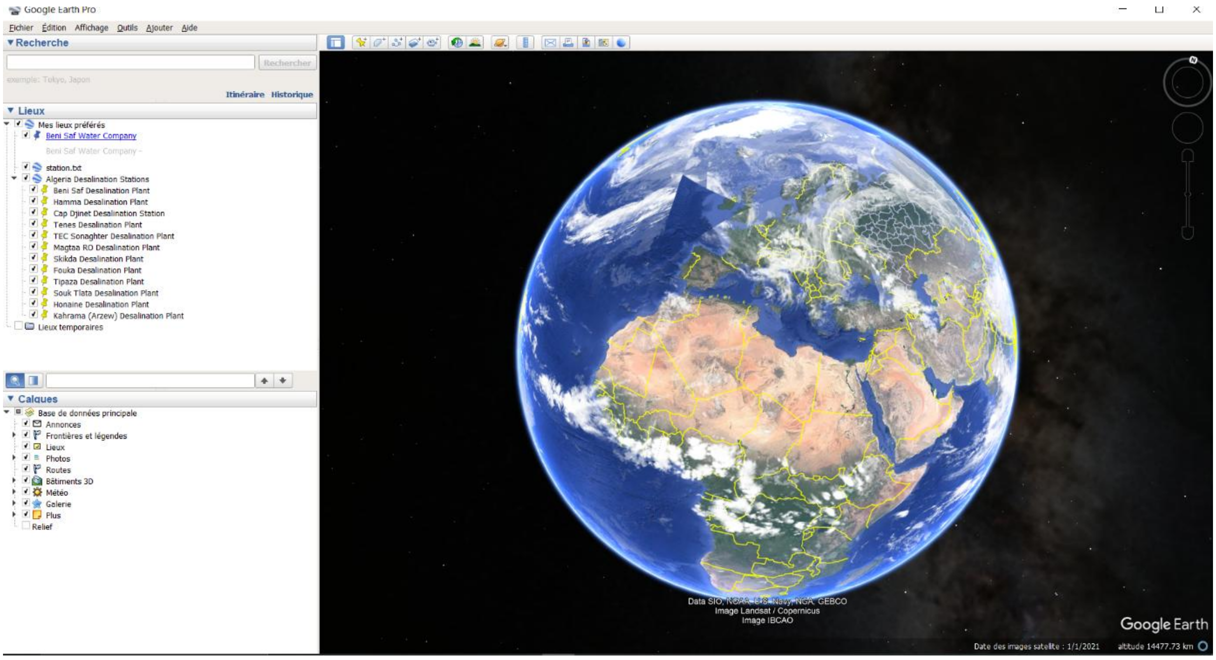
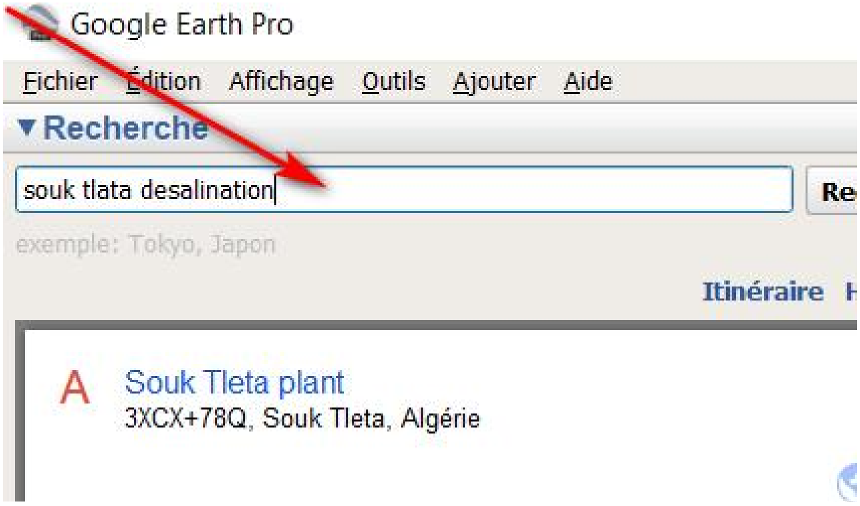


Figure 30 : Google Earth Pro

2. Search for the plant by name or by the nearest city or locality.

3. Visually confirm the plant's location by identifying key infrastructure elements (e.g., large pipelines, storage tanks, proximity to the coastline).



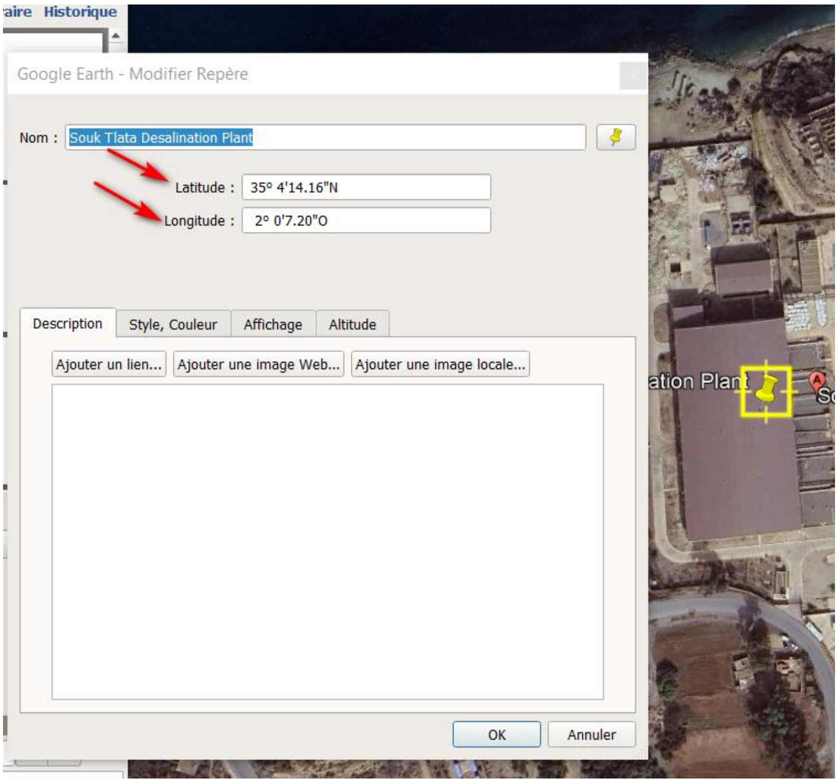
souk tlata desalination

A Souk Tleta plant
3XCX+78Q, Souk Tleta, Algérie

Figure 31 : search by name in google earth pro

Figure 32 : souk tlata desalination plant in google earth

4. Record the exact geographic coordinates (latitude and longitude). press the right button This image will appear to you:



Google Earth - Modifier Repère

Nom : Souk Tlata Desalination Plant

Latitude : 35° 4'14.16"N

Longitude : 2° 0'7.20"O

Figure 33:geographic coordinates of Souk Tlata desalination plant in google earth

5. Save the identified points in a **.KML** file format for use in GIS software.

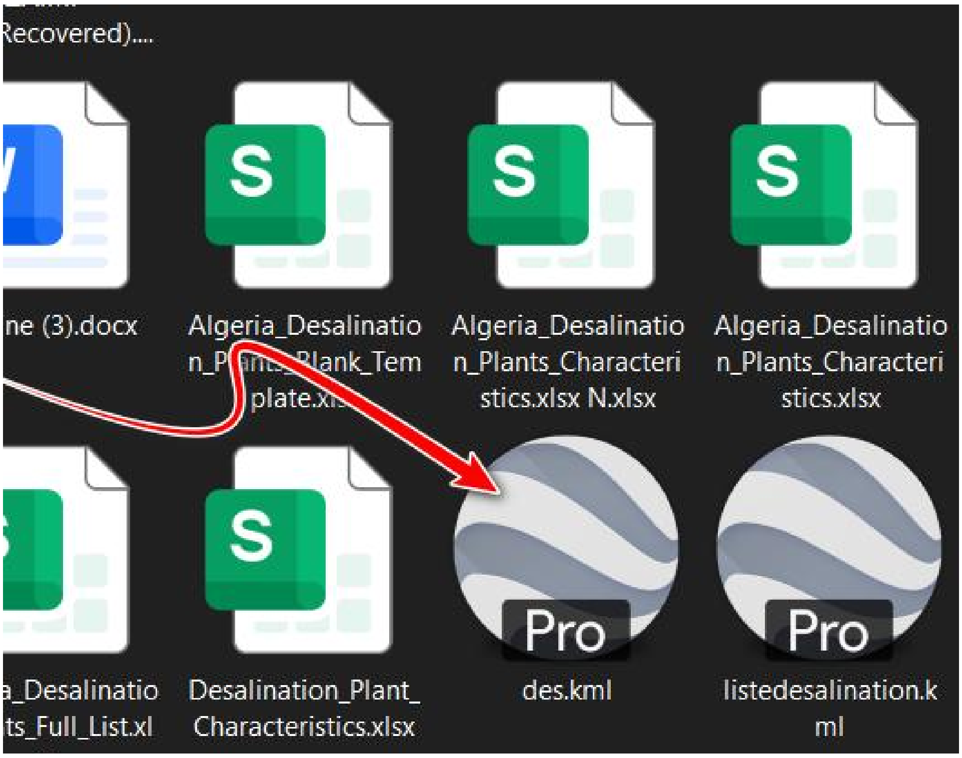


Figure 34: Export Points as a .KML File

2.1.3 Importing the Data into Global Mapper

Once the .KML file containing the plant locations was prepared, we used Global Mapper to begin building the geospatial database:

- Import the KML file :

File > Open Data File(s)... and select the .kml file.

- All plant location points appeared on the map.
- We then created a custom attribute table by using the Attribute Editor, where we added detailed information for each plant:

Producing Capacity, Alimentation Area, Etc.

Structuring and Formatting the Database

- All attribute fields were standardized and written in English.
- Data accuracy was double-checked against source materials.

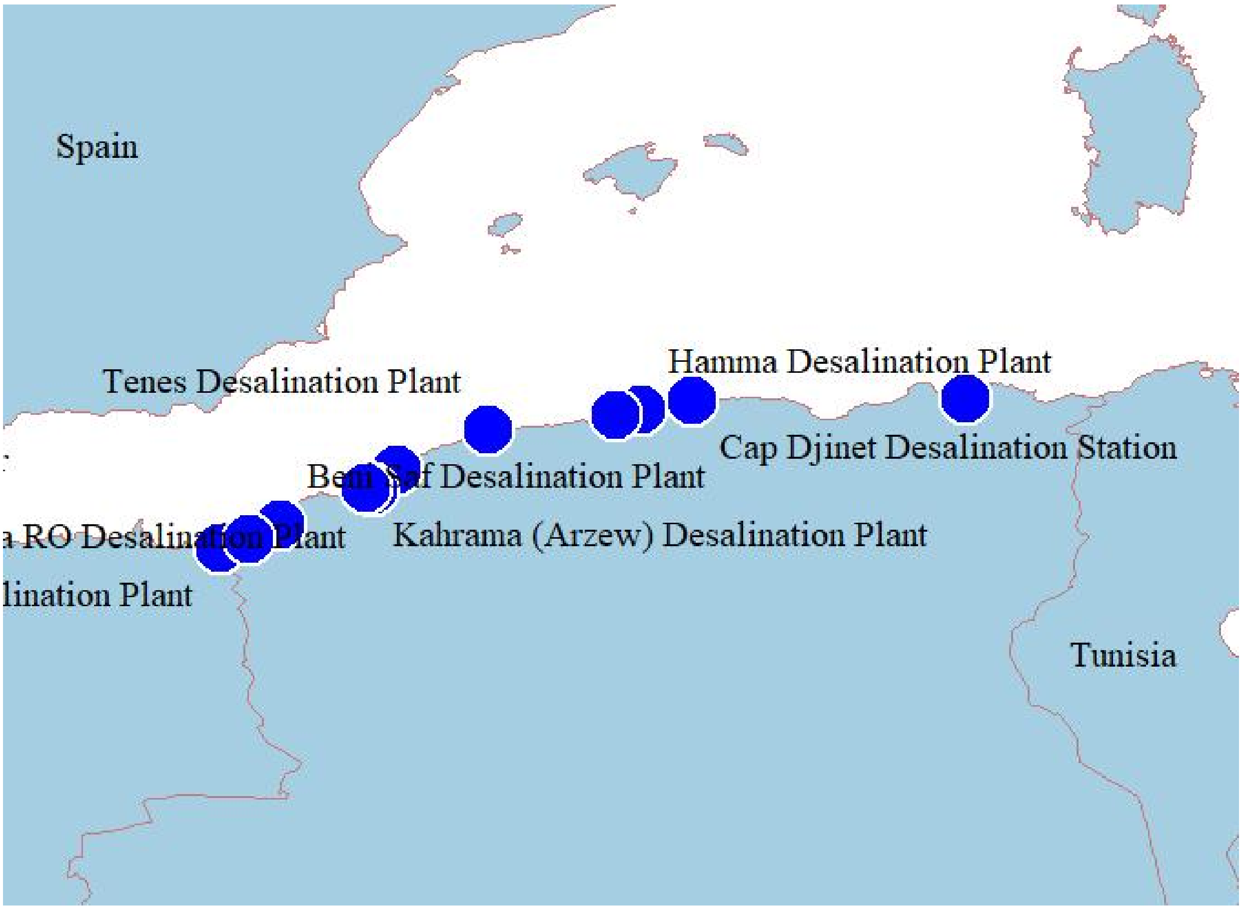


Figure 35: Spatial Assessment of Desalination Plants in the Algerian Coastal

Chapter 4

Exporting and Preparing Data for Analysis

1 Exporting and Preparing Data for Analysis

- After final validation, the complete geospatial database was exported.
- The final format used was Shapefile (.shp), ensuring compatibility with spatial analysis tools and further integration into the TOPSIS multi-criteria analysis model.
- Symbols and colors were assigned to each plant based on classification criteria such as capacity range or technology type.

We developed a Python script designed to calculate the ideal performance score of each desalination plant by comparing its characteristics against those of all other stations. This approach aligns with multi-criteria decision-making frameworks, such as the TOPSIS method, where relative performance is assessed based on proximity to an ideal solution.

1.1 Step 1: Construct the Decision Matrix

Start by creating a decision matrix that includes:

- Alternatives: Each desalination plant to be evaluated.
- Criteria: Performance indicators (e.g., water quality, capacity, energy use, etc.).

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

Figure 36:the TOPSIS desicion matrix

The matrix is structured as:

Where:

- xij is the performance value of alternative iii under criterion j,
- m = number of desalination plants,

- n = number of criteria.

1.2 Step 2: Normalize the Decision Matrix

Normalization is required to bring all criteria to the same scale. The normalized matrix R=[rij] is calculated using:

$$rij \quad = \frac{Xij}{\sqrt{\sum_{i=1}^{m} X^2 ij}}$$

This ensures comparability among criteria.

1.3 Step 3: Construct the Weighted Normalized Matrix

Multiply each normalized value by the weight of the corresponding criterion:

$$vji = wji\,.\; rij$$

Where :

- wj is the weight assigned to criterion j (based on its importance in desalination performance),
- vi is the weighted normalized value.

The result is the matrix V=[Vij]

1.4 Step 4: Determine the Ideal and Negative-Ideal Solutions

Identify :

1. Positive Ideal Solution (PIS) : Best possible performance.
2. Negative Ideal Solution (NIS): Worst possible performance.

- For benefit criteria (higher is better):

A^+ = {max (Vij)} (for benefit criteria), A^- = {min (Vij)}

- For cost criteria (lower is better):

A^+ = {min (Vij)} (for cost criteria), A^- = {max (Vij)}

These solutions are vectors that represent the optimal and worst conditions.

1.5 Step 5: Calculate the Separation Measures

Calculate the distance of each alternative from the ideal and negative-ideal solutions using Euclidean distance:

- Distance from ideal (PIS) :

$Si^+ = \sqrt{(\sum_{j=1}^{n} (Vij - Aj^+)^2)}$

- Distance from negative-ideal (NIS):

$Si^- = \sqrt{(\sum_{j=1}^{n} (Vij - Aj^-)^2)}$

Where $Si+$ and $Si-$ are the distances of the i-th plant from the ideal and negative-ideal solutions.

1.6 Step 6: Calculate the Relative Closeness to the Ideal Solution

Determine how close each plant is to the ideal solution:

$$Ci = \frac{Si^-}{Si^+ + Si^-}$$

Where :

- Ci is the relative closeness coefficient of plant i to the ideal solution,
- 0≤Ci≤10
- A higher Ci means better performance.

1.7 Step 7: Rank the Alternatives

Finally, rank the desalination plants based on their Ci values in descending order. The plant with the highest Ci value is considered the most efficient and best-performing among the alternatives.

1.8 Python script

We have developed a Python script that creates a simple graphical user interface (GUI) application using Tkinter to evaluate and rank water treatment stations based on multiple criteria using the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution)

What the program does :

1.8.1.1 Defines criteria for evaluation of stations:

- RO Treatment Performance (%) …benefit criterion (higher is better)
- Capital Cost (DZD) … cost criterion (lower is better)
- Production Capacity (m³/day) … benefit criterion
- Energy Consumption (kWh/m³) … cost criterion
- Plant Age (Years) … cost criterion

1.8.1.2 Allows the user to input data for multiple stations:

- Add new stations with a name and numeric values for each criterion.
- Edit existing station data (except the station name).

1.8.1.3 Stores stations and their criteria values in memory using two lists:

- stations: list of station names
- matrix: list of lists with criteria values per station

1.8.1.4 Runs the TOPSIS analysis when the user clicks "Run TOPSIS":

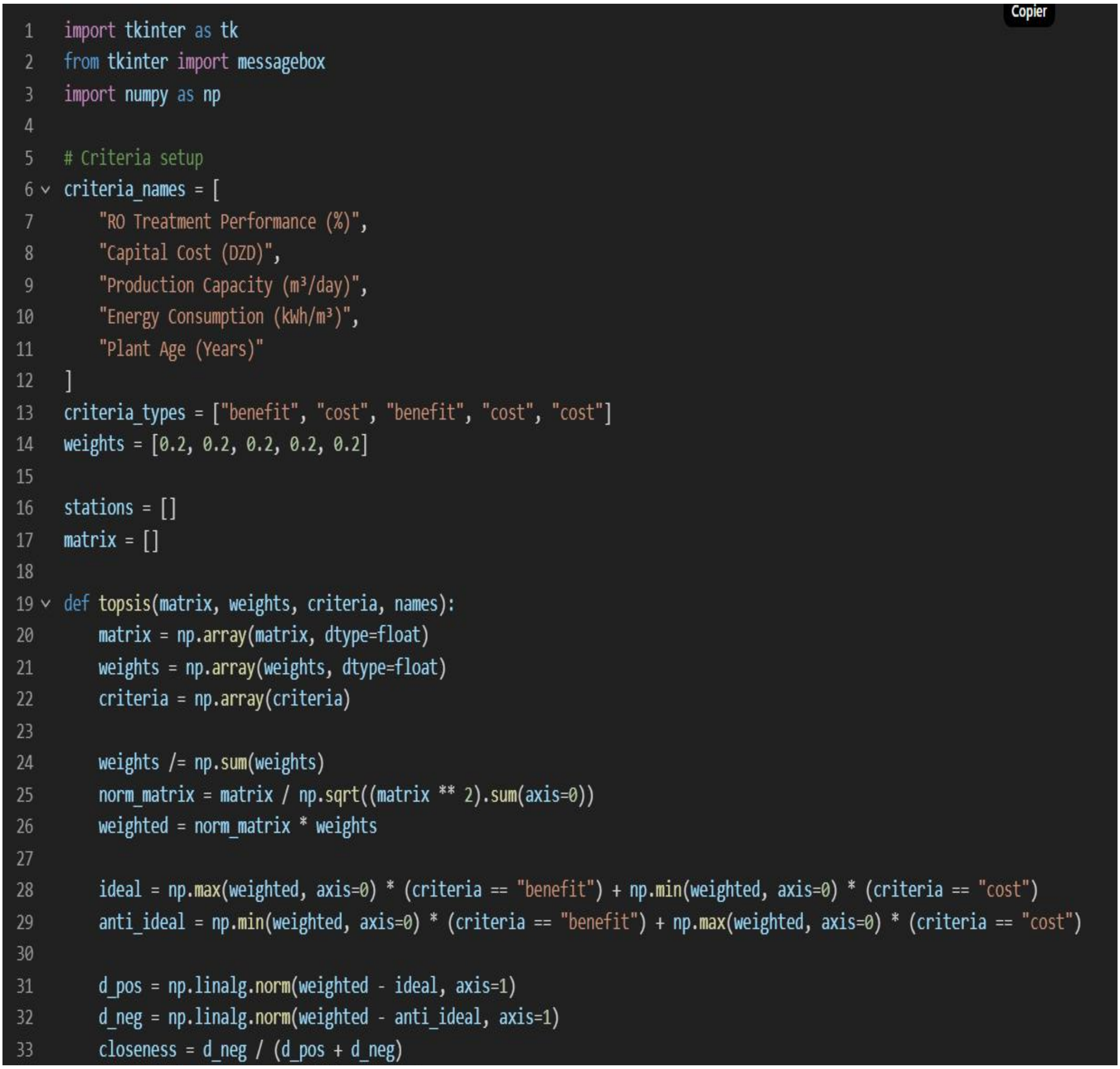
- Normalizes the decision matrix and applies weights.
- Identifies ideal (best) and anti-ideal (worst) solutions based on criteria types (benefit/cost).
- Calculates the Euclidean distance of each station to these ideal points.
- Computes a closeness coefficient indicating how close each station is to the ideal solution.
- Sorts and ranks the stations accordingly.

1.8.1.5 Displays the TOPSIS closeness scores and rankings in a text box.

The GUI consists of :

- Buttons to add a new station, edit a selected station, and run the TOPSIS evaluation.

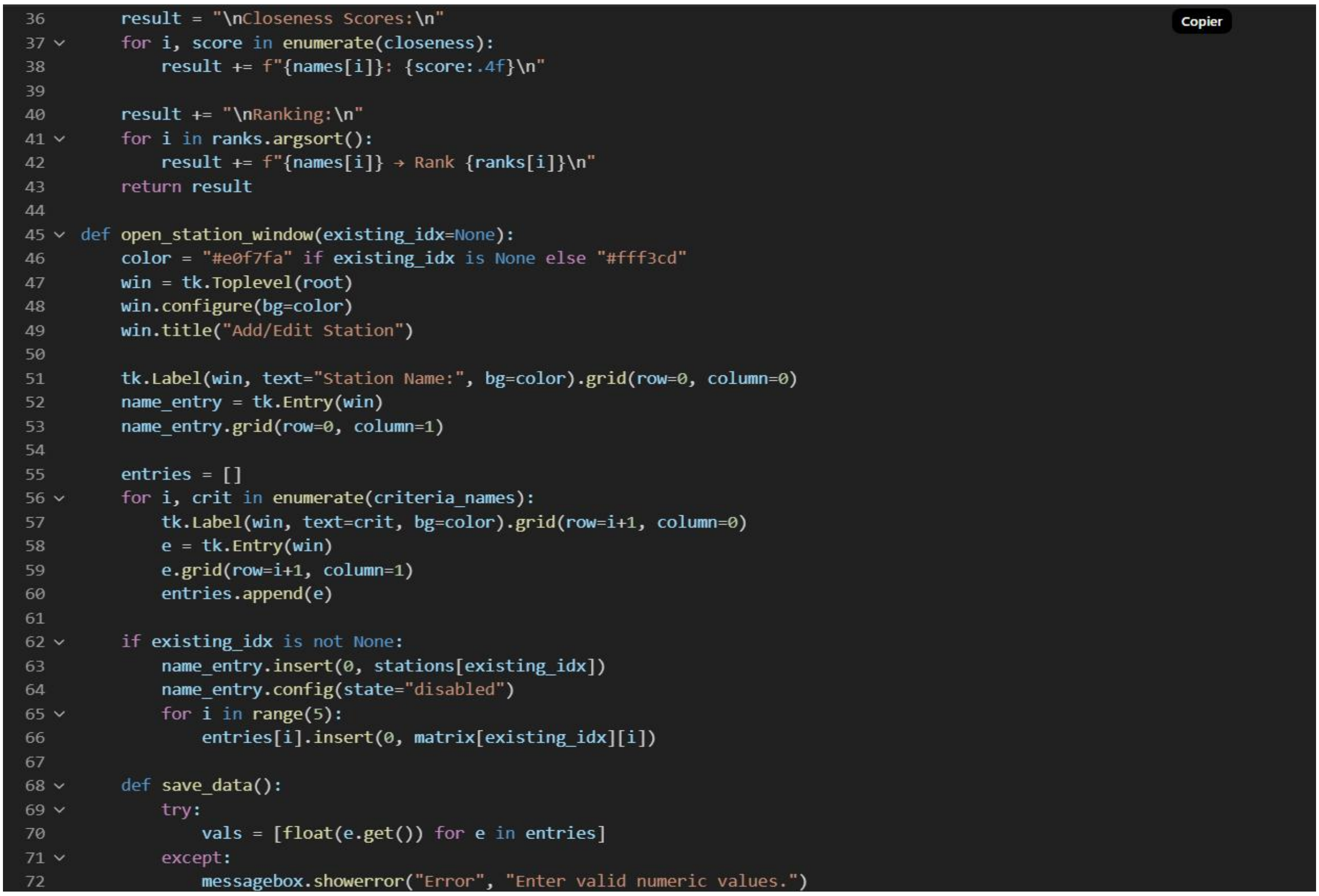
- A listbox showing all station names.
- A text area showing the TOPSIS results.



```python
import tkinter as tk
from tkinter import messagebox
import numpy as np

# Criteria setup
criteria_names = [
    "RO Treatment Performance (%)",
    "Capital Cost (DZD)",
    "Production Capacity (m³/day)",
    "Energy Consumption (kWh/m³)",
    "Plant Age (Years)"
]
criteria_types = ["benefit", "cost", "benefit", "cost", "cost"]
weights = [0.2, 0.2, 0.2, 0.2, 0.2]

stations = []
matrix = []

def topsis(matrix, weights, criteria, names):
    matrix = np.array(matrix, dtype=float)
    weights = np.array(weights, dtype=float)
    criteria = np.array(criteria)

    weights /= np.sum(weights)
    norm_matrix = matrix / np.sqrt((matrix ** 2).sum(axis=0))
    weighted = norm_matrix * weights

    ideal = np.max(weighted, axis=0) * (criteria == "benefit") + np.min(weighted, axis=0) * (criteria == "cost")
    anti_ideal = np.min(weighted, axis=0) * (criteria == "benefit") + np.max(weighted, axis=0) * (criteria == "cost")

    d_pos = np.linalg.norm(weighted - ideal, axis=1)
    d_neg = np.linalg.norm(weighted - anti_ideal, axis=1)
    closeness = d_neg / (d_pos + d_neg)
```

Figure 37 : Python script

The script is as follows:



```python
    result = "\nCloseness Scores:\n"
    for i, score in enumerate(closeness):
        result += f"{names[i]}: {score:.4f}\n"

    result += "\nRanking:\n"
    for i in ranks.argsort():
        result += f"{names[i]} → Rank {ranks[i]}\n"
    return result

def open_station_window(existing_idx=None):
    color = "#e0f7fa" if existing_idx is None else "#fff3cd"
    win = tk.Toplevel(root)
    win.configure(bg=color)
    win.title("Add/Edit Station")

    tk.Label(win, text="Station Name:", bg=color).grid(row=0, column=0)
    name_entry = tk.Entry(win)
    name_entry.grid(row=0, column=1)

    entries = []
    for i, crit in enumerate(criteria_names):
        tk.Label(win, text=crit, bg=color).grid(row=i+1, column=0)
        e = tk.Entry(win)
        e.grid(row=i+1, column=1)
        entries.append(e)

    if existing_idx is not None:
        name_entry.insert(0, stations[existing_idx])
        name_entry.config(state="disabled")
        for i in range(5):
            entries[i].insert(0, matrix[existing_idx][i])

    def save_data():
        try:
            vals = [float(e.get()) for e in entries]
        except:
            messagebox.showerror("Error", "Enter valid numeric values.")
```

Figure 39:Python script

```python
            return

        name = name_entry.get()
        if not name:
            messagebox.showwarning("Missing Name", "Enter a station name.")
            return

        if existing_idx is not None:
            matrix[existing_idx] = vals
        else:
            stations.append(name)
            matrix.append(vals)
        update_listbox()
        win.destroy()

    tk.Button(win, text="Save", command=save_data, bg="#ade8f4").grid(row=6, column=0, columnspan=2, pady=10)

def update_listbox():
    station_list.delete(0, tk.END)
    for name in stations:
        station_list.insert(tk.END, name)

def run_topsis():
    if len(matrix) < 2:
        messagebox.showinfo("Need More", "Enter at least two stations.")
        return
    result = topsis(matrix, weights, criteria_types, stations)
    output_text.delete(1.0, tk.END)
    output_text.insert(tk.END, result)

def edit_selected():
    idx = station_list.curselection()
    if not idx:
        messagebox.showinfo("No Selection", "Select a station to edit.")
        return
    open_station_window(idx[0])
```

```
# GUI
root = tk.Tk()
root.title("TOPSIS Evaluator")
root.geometry("750x500")
root.configure(bg="#d6f5f5")

frame = tk.Frame(root, bg="#d6f5f5")
frame.pack(pady=10)

tk.Button(frame, text="Add Station", bg="#caffbf", command=open_station_window).pack(side=tk.LEFT, padx=10)
tk.Button(frame, text="Edit Station", bg="#ffd6a5", command=edit_selected).pack(side=tk.LEFT, padx=10)
tk.Button(frame, text="Run TOPSIS", bg="#9bf6ff", command=run_topsis).pack(side=tk.LEFT, padx=10)

station_list = tk.Listbox(root, height=6, width=60)
station_list.pack(pady=10)

output_text = tk.Text(root, height=15, width=90)
output_text.pack(pady=10)

root.mainloop()
```

Figure 40: Python script

1.9 application

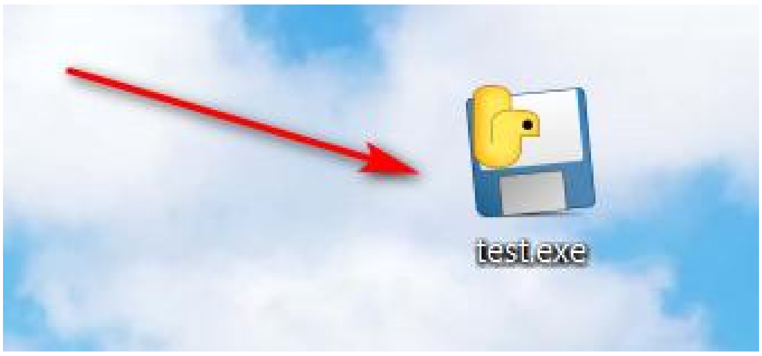
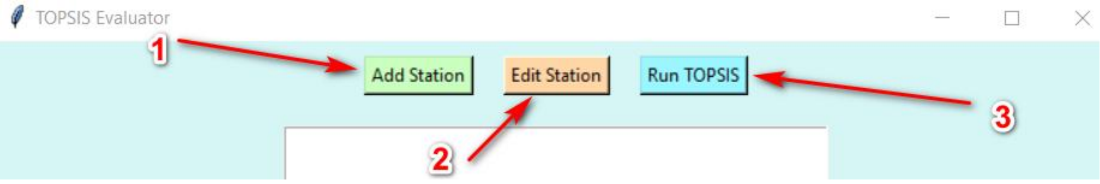


Figure 42:the topsis program on desktop

Figure 41an opening topsis program

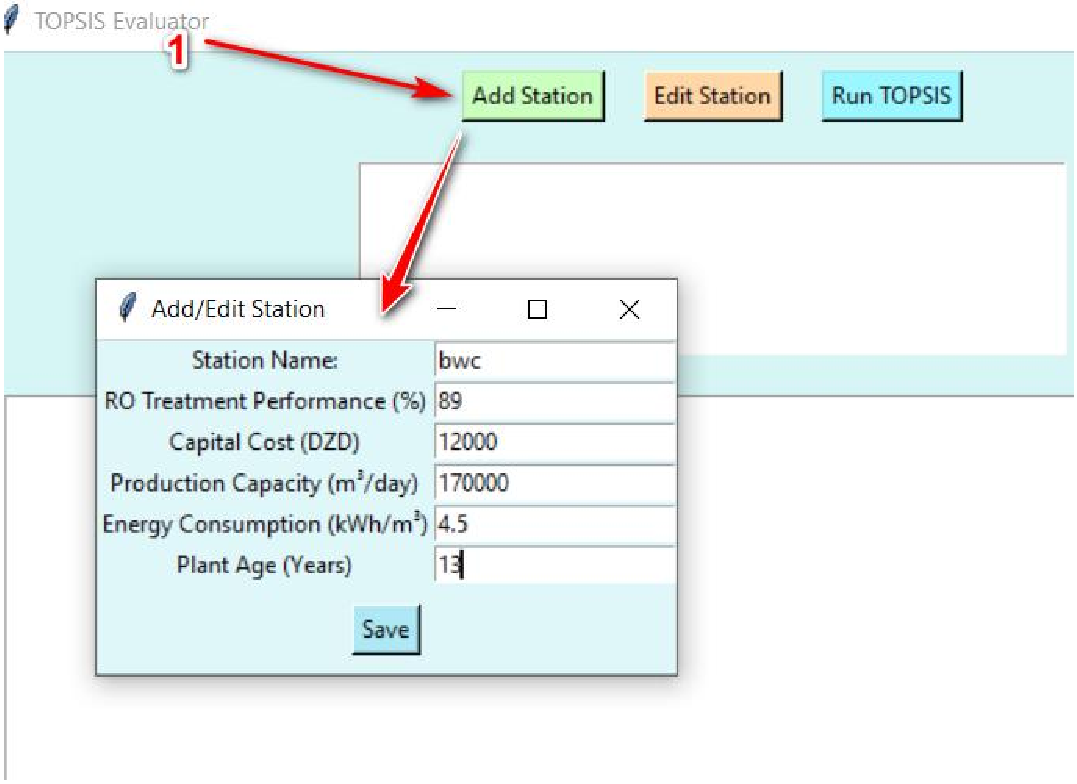


open the program:

1.9.1 Step 1 : Add Station

- Function**:** This step allows the user to enter information about a new desalination plant (station).
- Action**:** When you click the "Add Station" button, a form or dialog likely appears where you input various characteristics such as capacity, energy use, location, etc.

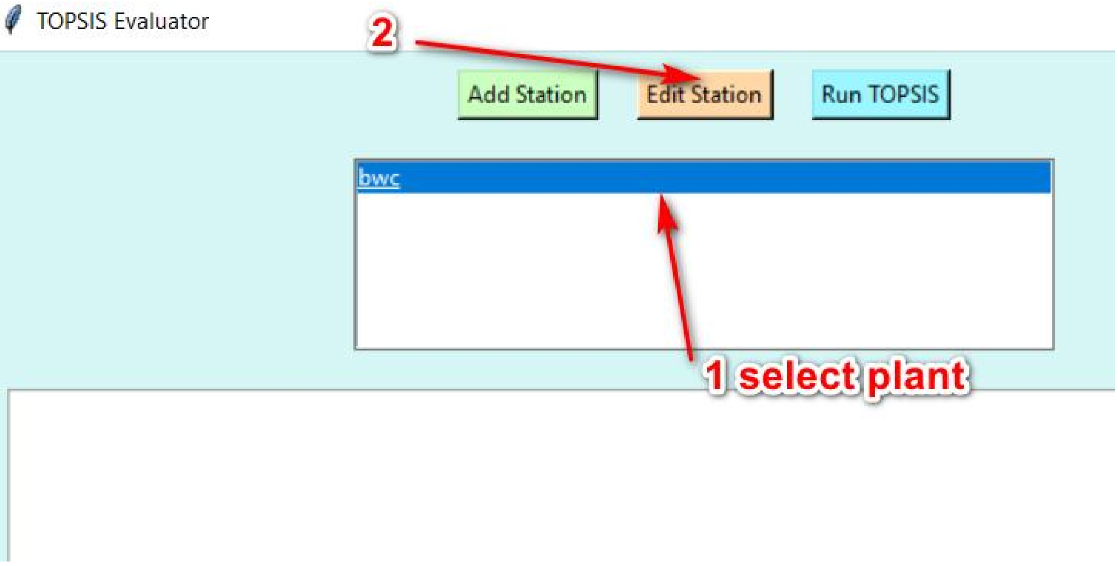
- Purpose: This data is necessary to later evaluate and compare the performance of each plant using the TOPSIS method.



Station Name: bwc
RO Treatment Performance (%) 89
Capital Cost (DZD) 12000
Production Capacity (m^3/day) 170000
Energy Consumption (kWh/m^3) 4.5
Plant Age (Years) 13

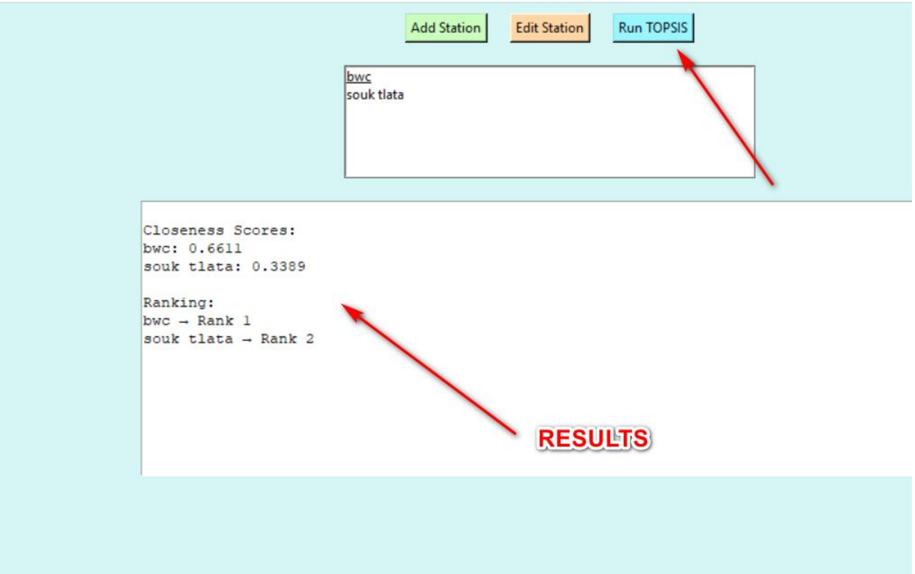
1.9.2 Step 2 : Edit Station

- Function: This step lets you modify or update the information of an existing station already added to the system.
- Action: By clicking "Edit Station", you can select a plant and adjust its criteria (e.g., if you want to correct a value or update performance data).
- Purpose: Ensures that all station data is accurate and up to date before running the analysis.



1.9.3 Step 3 : Run TOPSIS

- Function: This is the core analysis step using the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method.
- Action: When you click the "Run TOPSIS" button, the software uses the entered data to calculate a score for each station based on multiple criteria.
- Purpose: It ranks the stations from best to worst, helping decision-makers choose the most optimal plant(s) according to the selected criteria.



```
Closeness Scores:
bwc: 0.6611
souk tlata: 0.3389

Ranking:
bwc → Rank 1
souk tlata → Rank 2
```

2 Discussion

The integration of the TOPSIS decision-making model with a GIS-supported framework, like that offered by Global Mapper, creates a strong synergy between spatial data management and multi-criteria performance evaluation. This combined approach not only allows for the visualization of desalination infrastructure along Algeria's coastal zones but also supports evidence-based decision-making for future development, optimization, and policy planning.

2.1 Spatial Analysis and Data Integration

Using Global Mapper, we accurately geolocated all desalination plants by utilizing both field-verified GPS coordinates and high-resolution satellite imagery from Google Earth Pro. By importing this spatial data as KML files in Global Mapper, we created a layered representation that included physical locations, infrastructure connectivity, and environmental context. This geospatial visualization revealed clear patterns in the distribution of the plants, emphasizing their strategic coastal positioning near urban and industrial hubs such as Oran, Algiers, and Skikda. It also highlighted gaps in coverage and logistical inefficiencies in certain regions.

The attribute data compiled and organized in Global Mapper, which includes metrics such as production capacity, energy consumption, plant age, and reverse osmosis performance, served as the foundation for the decision matrix used in the TOPSIS analysis. By structuring the dataset with standardized fields, we ensured compatibility with a subsequent Python-based decision support tool, allowing for objective cross-comparison.

2.2 Performance Evaluation with TOPSIS

The TOPSIS algorithm, implemented through a custom-built Python GUI application, was a crucial tool in translating raw operational data into actionable insights. By evaluating each desalination plant across multiple criteria, this method enabled the quantification of efficiency, sustainability, and cost-effectiveness relative to an ideal solution.

The use of both benefit and cost criteria (e.g., RO performance and capacity as benefits, vs. capital cost and energy consumption as costs) aligns with real-world priorities in water infrastructure: maximizing clean water output and quality while minimizing financial and environmental burdens. Normalization and weighting ensured that the criteria were treated appropriately, and the calculation of closeness coefficients (Ci values) provided a clear ranking of alternatives.

2.3 Key findings from the analysis :

Newer plants, such as *Fouka 2* and *Cap Blanc*, tend to perform better overall due to modern reverse osmosis (RO) technologies, higher capacity, and improved energy recovery systems, despite their high capital costs.

Older facilities, such as Souk Tleta and Zéralda (in its original 2010 version), were comparatively less efficient, especially when maintenance or partial operation (e.g., Souk Tleta’s reduced output) diminished their performance.

Plants such as *Beni Saf* demonstrated high RO efficiency and strong infrastructure integration, ranking highly despite moderate energy consumption, due to their strategic location and operational reliability.

Conversely, smaller-scale units, such as Bou Ismaïl and Zéralda (low-capacity variants), although technically compliant, were limited in their regional impact due to their lower production volumes.

2.4 Decision-Making Implications

This analysis supports several key policy and planning implications:

Expansion and Rehabilitation: Priority should be given to upgrading older desalination plants with poor performance scores through retrofitting, improved energy integration, and operational optimization.

Strategic Siting for New Infrastructure: Utilizing GIS maps and performance rankings, new desalination plants can be sited in underserved areas while ensuring optimal performance parameters based on the TOPSIS criteria.

Energy Considerations: With energy consumption as a significant cost driver, promoting integration of renewable energy systems (which was largely absent across the dataset) could enhance sustainability.

Standardized Monitoring: The methodology introduced could serve as a national benchmarking tool for desalination plant performance, enabling real-time performance audits and long-term strategic planning.

2.5 Limitations and Future Enhancements

While robust, the current system has some limitations:

Not all data were available for every plant (e.g., pump efficiency, real-time output vs. design capacity), which may affect comparative accuracy.

The weighting of criteria in the TOPSIS model was applied generically; in future iterations, these weights could be refined through expert consultation or stakeholder input to reflect region-specific priorities (e.g., water scarcity severity, cost constraints).

The lack of renewable energy data suggests a blind spot in environmental performance assessments.

By combining spatial analysis with quantitative performance evaluation, this thesis provides a comprehensive, data-driven approach to understanding and improving desalination infrastructure in Algeria. The use of Global Mapper for geospatial mapping and a Python-based TOPSIS model for performance ranking exemplifies how fieldwork, GIS, and decision science can converge to support sustainable water resource management. This methodology can be replicated or expanded to other regions facing similar water scarcity challenges, thereby further reinforcing the value of integrated GIS decision support systems in environmental engineering and infrastructure planning.

General conclusion

This thesis addresses the growing pressure on water resources, especially in Algeria, where freshwater scarcity necessitates the adoption of alternative solutions. A key objective of this work was to enhance the management of seawater desalination plants by developing a comprehensive spatial and technical database integrated within a Geographic Information System (GIS) environment. Additionally, a decision-support application based on the TOPSIS method was created to aid in this management process.

The adopted methodology was structured around three core components: the collection and organization of technical and spatial data related to Algeria's desalination plants, the integration of this data into the Global Mapper software to produce detailed geographic visualization, and the development of an interactive Python-based application using Tkinter, capable of applying the TOPSIS method for multi-criteria evaluation. This work's originality lies in combining a GIS-based database with a user-friendly decision-making interface that is adaptable to different configurations and customizable criteria.

The resulting tool allows for dynamic ranking of desalination plants based on a wide range of technical, environmental, or logistical criteria. Though it does not aim to assess the current performance of existing plants, it offers a reliable framework that can support future performance evaluations, depending on updated or newly acquired data.

The efforts made in this project demonstrate a commitment to innovation through the integration of spatial technologies and decision-analysis methods. Future enhancements could include :

- The integration of real-time performance data,
- The expansion of the database to include environmental or financial indicators,
- The adoption of more advanced visualization libraries to further improve the graphical interface.

In conclusion, this work makes a significant contribution to the advancement of digital tools that support sustainable water resource management in Algeria. By integrating Geographic Information Systems with multi-criteria decision-making methodologies such as TOPSIS, it provides a practical and innovative framework that enhances the planning, monitoring, and evaluation of seawater desalination projects. Beyond its immediate application, the system developed in this thesis serves as a foundational platform for future expansion and refinement, offering a flexible and scalable solution that can be adapted to evolving technical, environmental, and socio-economic criteria. Ultimately, this approach aims to empower decision-makers with reliable, data-driven insights, thereby promoting more informed, transparent, and strategic interventions in the field of desalination infrastructure and broader water resource governance.

Bibliography

ANRH. (2022). *Rapport annuel sur les ressources en eau et les infrastructures hydrauliques en Algérie.* . ORAN: – Agence Nationale des Ressources Hydrauliques.

arcgis. (2025, 4 27). *arcgis*. Retrieved from www.arcgis.com: https://www.arcgis.com/home/item.html?id=c39310050f6247bc991b94238fcb27af&utm_source=chatgpt.com

Association, I. D. (2025, 4 28). *idrawater*. Retrieved from www.idadesal.org: https://idrawater.org/

Bank., W. (2018). *Beyond Scarcity: Water Security in the Middle East and North Africa.World Bank. (2018). Beyond Scarcity: Water Security in the Middle East and North Africa.* Washington, DC:: World Bank.

barkadesalination. (2025, 4 28). *barkadesalination*. Retrieved from www.barkadesalination.com: https://www.barkadesalination.com/articles/article-11jul-18

BRAM-cor. (2025, 4 27). Retrieved from vapor-compression-distiller.com/: https://vapor-compression-distiller.com/vapor-compression-distiller-process

Burrough, P. M. (1998). *Principles of Geographical Information Systems.* Oxford: : Oxford University Press.

BWC. (2025, 4 28). *beni saf water comoany*. Retrieved from benisafwatercompany.dz: https://benisafwatercompany.dz/station/

Cambridge. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge.

CAREWATER. (2025, 4 27). *carewater*. Retrieved from carewater.solution: https://carewater.solutions/

Clarke, K. (2003). *Getting Started with Geographic Information Systems* (4TH ed ed.). Upper Saddle River,.

Darwish, M. A.-N. (2005). A review of the development and application of desalination processes in the Middle East. *Desalination:*, 184(1-3), 191-206.

Drioli, E. (2011). *Thermal Desalination Processes.*

Drioli, E. (2020). *Thermal Desalination Processes.* Springer. .

El-Dessouky. (2002). *Fundamentals of salt water desalination.*

ENKA. (2025, 427). *ENKA*. Retrieved from ENKA.COM: https://www.enka.com/portfolio-item/zawia-dealination-plant-project/

Environmental Challenges of Seawater Desalination. (2020). *Water Research Journal*, 173.

Geographics, B. M. (2023, 4 9). *Blue Marble Geographics*. Retrieved from Blue Marble Geographics.com: https://www.bluemarblegeo.com/knowledgebase/global-mapper-24-1/

Ghaffour. (2013). Current and future challenges for better water supply sustainability. Desalination,. *Technical review and evaluation of the economics of water desalination*, 309, 197–207.

Group, I. M. (2025, 4 24). *Utilities Middle East*. Retrieved from https://www.utilities-me.com/: https://www.utilities-me.com/news/17667-privatisation-of-saudis-ras-al-khair-desalination-and-power-plant-halted

GWI, G. W. (2024, 4 13). *Desalination plant profiles in Algeria. Retrieved*. Retrieved from Global Water Intelligence: [https://www.globalwaterintel.com]

IRENA. (2025, 4 27). *International Renewable Energy Agency*. Retrieved from https://www.irena.org/.

Kazmerski, A.-K. (2013).

Longley, P. G. (2015). *Geographic Information Systems and Science.* NJ: Wiley.: Hoboken.

MARLO-INC. (2025, 4 29). *MARLO-INC*. Retrieved from https://www.marlo-inc.com/: https://www.marlo-inc.com/news/1000-gpm-reverse-osmosis-ro-system

masdar. (2025, 4 27). *masdar*. Retrieved from masdar.ae: https://masdar.ae/en/renewables/our-projects/ghantoot-desalination-pilot-plant

Mitiche, R. (2010). Desalination and Water Treatment 14. 259–264.

Muller, H. B. (2018). "Performance analysis of a vapor compression distillation system for seawater desalination.". *Journal of Membrane Science.*

NEOM. (2025, 5 09). *neom*. Retrieved from neom.com: https://www.neom.com/en-us/sectors/water

NIDAL.H. (2021). *Nanofiltration for Sustainability.* CRC Press.

SATA, T. (2004). *Ion Exchange Membranes: Preparation, Characterization, Modification and Application.* Cambridge: The Royal Society of Chemistry.

sciencedirect. (2025, 05 07). *sciencedirect*. Retrieved from sciencedirect.com: https://www.sciencedirect.com/journal/desalination/vol/309/suppl/C

Shafique, M. K. (2019). *Desalination: Methods and processes. Elsevier.*

State of Alaska Geoportal. (2025, 427). Retrieved from gis.data.alaska.gov: https://gis.data.alaska.gov/datasets/SOA-DNR::trans-alaska-pipeline/explore?location=64.647409%2C-133.496099%2C4.20

Strathmann, H. (2010). *Introduction to Membrane Science and Technology.* Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA.

Tanaka, Y. (2015). *Ion Exchange Membranes.* IEM Research, Ibaraki, Japan: Elsevier Science.

UNESCO. (2015).

UTILITIES, M. E. (2025, 4 24). *MIDDLE EAST UTILITIES*. Retrieved from https://www.utilities-me.com/: https://www.utilities-me.com/news/17667-privatisation-of-saudis-ras-al-khair-desalination-and-power-plant-halted

Veoliawatertechnologies. (2025, 4 26). *veoliawatertechnologies*. Retrieved from veoliawatertechnologies: https://www.veoliawatertechnologies.com/en/technologies/multiple-effect-distillation-med-tvc

Zrelli, A. (2025, 06 3). *researchgate*. Retrieved from researchgate.net: https://www.researchgate.net/figure/Diagram-of-a-multistage-flash-distillation-MSF-unit-14_fig2_318073890