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ARTICLE

Desalination Brine Discharge in Morocco

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ABSTRACT

Seawater desalination has been considered an important solution for water scarcity in coastal areas. Morocco, with its 3,500 km long coastline, has seen significant growth in population and industrial activities in recent years. The dams that supply water to most regions of Morocco have faced periods of drought. This led the government to start a large-scale seawater desalination project that shall produce over 2 MM m^3/year. The most common environmental impact associated with desalination plants is the high concentration brine discharge which can alter the physical, chemical, and biological properties of the receiving water body, In fact, the increasing number of desalination plants along the coastline amplifies the potential risks that brine discharges pose to marine ecosystems. This highlights the critical need for regulations to manage pollutant concentrations in water, both at the discharge point (Effluent Standards - ES) and in the receiving environment (Ambient Standards - AS). Law 36-15, in its Article 72, grants any natural or legal person, whether public or private, the right to carry out seawater desalination to meet their own water needs or those of other users, in accordance with current legislation and regulations. However, the definition of regulations concerning marine environmental aspects and the substantial limits for discharges has not yet been specified. Indeed, these regulations will need to be developed with due consideration for the local biodiversity. These regulations should also take into account the technical criteria required to determine the compliance point and define the boundaries of the brine discharge impact zone.

Keywords: Drought; Desalination; Environmental Impact; Brine Discharge; Regulations; Marine

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1. Introduction

Morocco, located in a semi-arid region south of the Mediterranean, is highly vulnerable to the impacts of climate change. This vulnerability is reflected in increasing temperatures and more frequent episodes of intense rainfall. From 1981 to 2020, the national average temperature rose significantly, exceeding 1.4 °C. Additionally, total precipitation declined by an estimated 20% between 1960 and 2018.

The intensification of droughts, exacerbated by climate change, has led to chronic water shortages in many hydraulic basins, negatively affecting all water-dependent sectors. Prolonged periods without rainfall are identified as the main drivers of both soil (edaphic) and hydrological droughts. Assessments by the Ministry for Water indicate that, factoring in climate change, Morocco's water basins could face a deficit of 7 billion cubic meters (MMm^3) by 2050.

Water resources in Morocco have become very limited and are characterized by an irregular geographical distribution. Therefore, resorting to the exploitation of non-conventional resources has become imperative [1].

In this context, and to combat the phenomenon of drought, the Moroccan government has adopted the following actions [2]:

- The supply of drinking water to coastal cities will be carried out through desalination plants.
- Existing and planned conventional resources will be dedicated to meeting the drinking water and irrigation needs of continental cities.
  Resorting to water transfer between hydraulic basins to create a balance of water resources in different regions, such as the transfer of water from the Sebou basin to the Oum Er-Rbia basin, which has around fifteen large dams. The regulated water volume for the Sebou basin is around 3,230 million m^3, compared to 240 million m^3 for the Oum Er-Rbia basin [3].
- Recharge of aquifers by limiting the overexploitation of these freshwater resources.
- Motivating the industrial sector to source its water supply from desalination (coastal cities).

Morocco has a long coastline (about 3,500 km) with two seafronts: the Mediterranean Sea (about 500 km) to the north and the Atlantic Ocean (about 3,000 km) to the west [4].

Positioned in upwelling zones (where nutrient-rich deep and cold waters rise), these coasts serve as migration routes for numerous species of ecological and economic interest [5]. This grants our country a more crucial and determining role in protecting its national marine fauna [6].

This positioning will facilitate water supply through desalination techniques in order to meet the growing demand for drinking water and ensure the necessary water for agriculture [7].

Indeed, desalination of seawater has become a crucial solution to address water scarcity in Morocco. The country faces significant challenges due to limited water availability, approaching the critical threshold of absolute water scarcity set at 500 m^3 per person per year [1]. Desalination can provide an essential additional water source in these contexts of severe water stress.

Desalination of seawater can be achieved using thermal or membrane techniques [7]. Reverse Osmosis (RO) is considered the most reliable method due to its low energy consumption and seawater usage. This process involves applying pressure greater than the natural osmotic pressure on the feed water through a semi-permeable membrane, allowing retention of salts and minerals while discharging them into the reject stream [8].

Using the reverse osmosis process, the concentrate will be doubly loaded with minerals, primarily salts, compared to the water entering the osmosis units. Studies have shown that this increase in salinity can negatively affect the morphological characteristics of certain marine species [9].

The environmental challenge that remains for the desalination industry lies in the residual effects during operation, particularly in the methods required to minimize the impact of brine on marine life.

2. Method

2.1. Define the Flow Rate of Water Produced by Desalination Plants

The number of desalination plants in Morocco has significantly increased over the past two decades [10]. Consequently, the discharge of brine has also increased, necessitating a quantitative and qualitative assessment of its impact on the marine environment.

The following **Figure 1** shows the brine discharge points of desalination plants in Morocco, taking into account future forecasts and a conversion rate of 45%[11, 12].

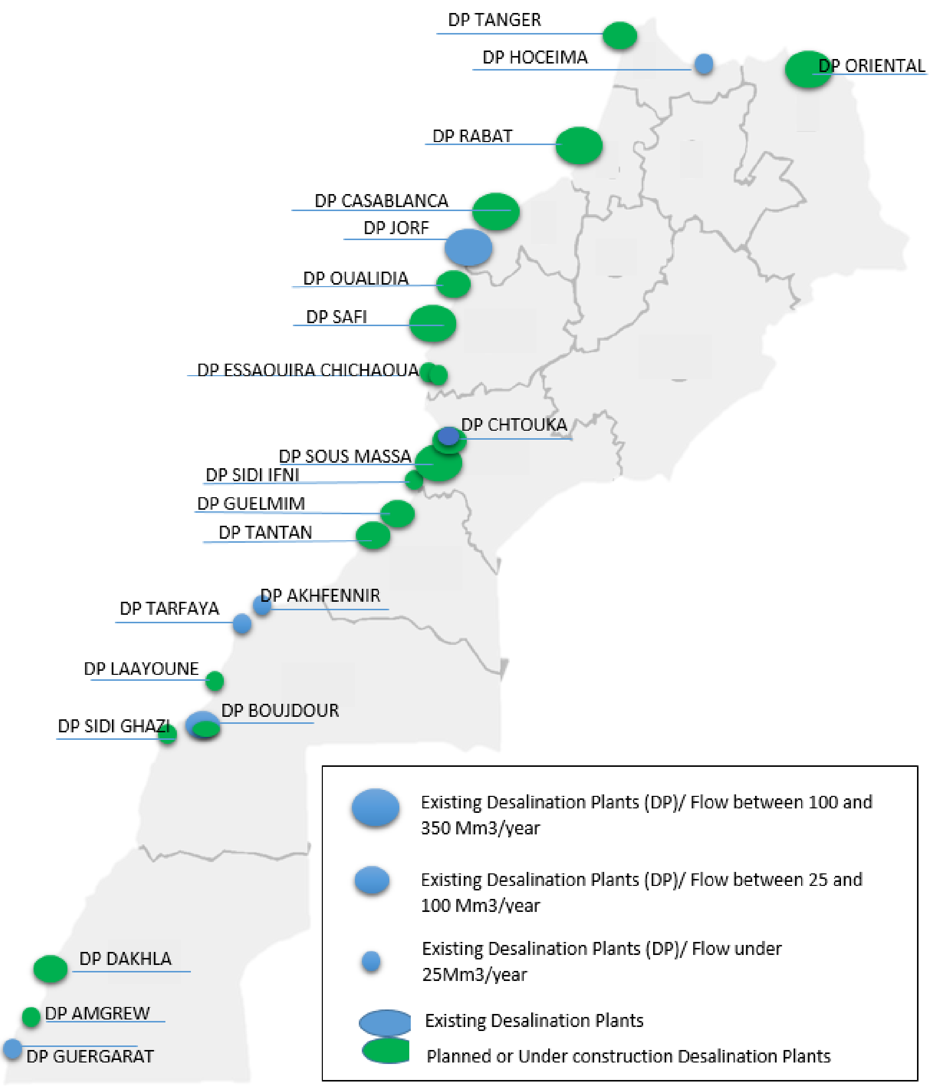


Figure 1. Brine discharge points of desalination plants in Morocco (existing and projected).

2.2. Define the Flow Rate of Brine Discharge Produced by Desalination Plants

The following graph, in the **Figure 2**, shows the projected brine situation by 2045, taking into account the current situation and a conversion rate of 45%.

As shown in **Figures 2** and **3**, the annual volume of brine discharges into the Mediterranean Sea is projected to reach 1 billion m^3 by 2045, compared to 14 million m^3 in 2024. This significant increase in discharges into a semi-enclosed sea will inevitably have negative impacts on the marine ecosystem. Given that all Mediterranean countries are suffering from water shortages due to drought, desalination remains their only viable alternative. This implies that the Mediterranean will experience a substantial rise in salinity, further exacerbated by the natural evaporation of seawater.

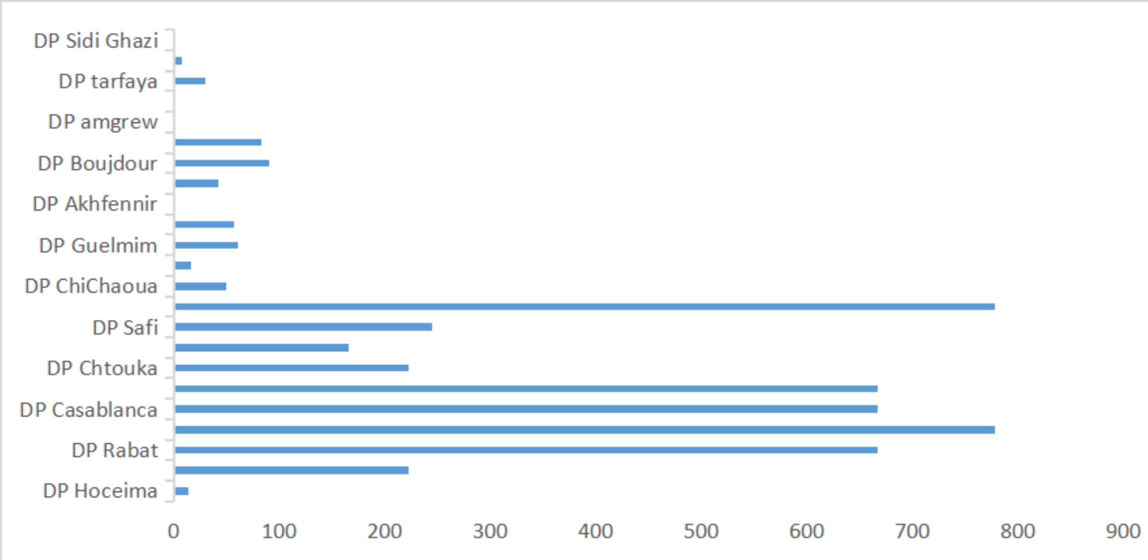


Figure 2. Brine Discharge from desalination plants by 2045 in Mm^3 per year.

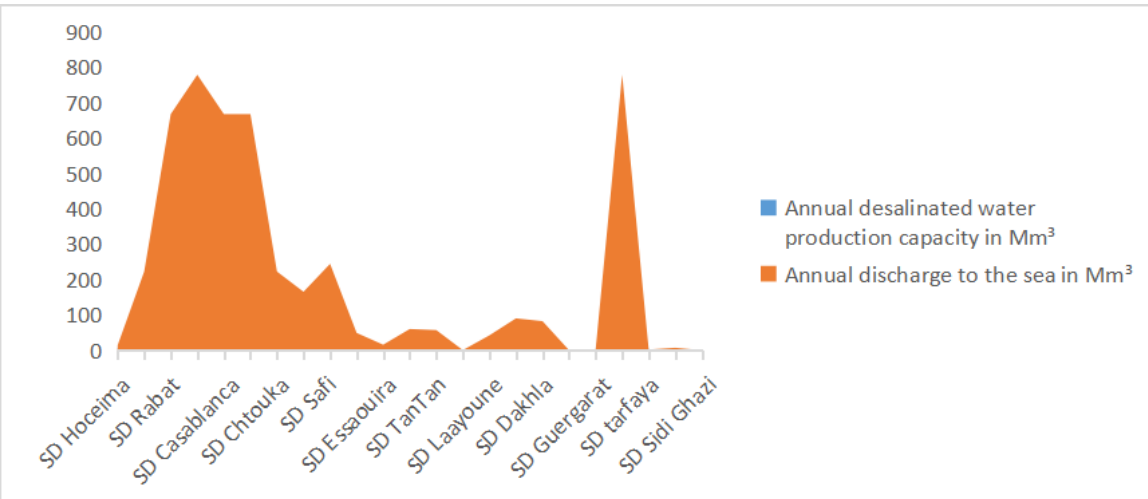


Figure 3. Annual desalinated water production and brine discharge to the sea in Mm^3.

2.3. Distribution of Brine Discharges Across the 12 Regions of Morocco

Therefore, it is essential to conduct a regional study to assess this impact on the Mediterranean, taking into account all desalination projects planned by Mediterranean countries, whose brine discharges are released directly or through outfalls along the coastline.

Regarding the Atlantic Ocean, the discharge volume is expected to reach 4.8 billion m^3 per year by 2045, compared to 960 million m^3 in 2024.

Discharge points, distributed along the coastline, vary by region. **Figure 4** shows that the Casablanca-Settat and Souss Massa regions alone account for approximately 50% of the total discharge volume. This is due to the significant industrial and agricultural activities that characterize these two major urban centers.

This increase in brine discharge has a direct impact on marine ecosystems, as the high salt concentration can disrupt aquatic fauna and flora.

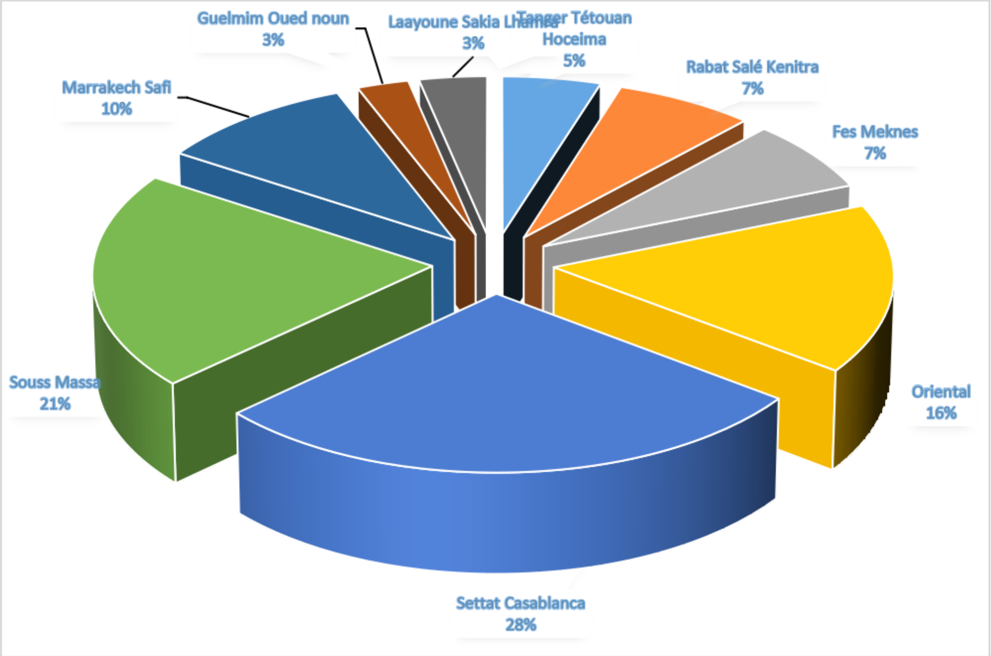


Figure 4. Brine discharge along the coastal regions of Morocco.

3. Results and Discussion

After presenting the existing and planned desalination plants in Morocco, the discharge flow to be released into the sea, as well as the distribution of these plants along the coastline by region, it was emphasized that this distribution is primarily determined by the specific water needs of each region.

3.1. Selection of Potential Sites for Desalination Plants

The selection of suitable sites for desalination plants is based on several essential criteria, including the following:

3.1.1. Identifying Water-Deficient Areas

Priority is given to regions where water demand exceeds the volume available from existing resources, making desalination a necessary alternative. For example, the Oum Er-Rbia basin, which serves as the primary water source for the Greater Casablanca-Settat and Marrakech-Safi regions, has experienced a significant decline in water levels, currently holding about 240 million m³ compared to 4.45 billion m³ in 2010. To address this shortfall, desalination plants along the coastline of these two regions are planned, with a combined annual capacity of approximately 780 million m³. Additionally, a major water transfer project from the Sebou basin, providing an annual volume of 186 million m³, is also under consideration.

3.1.2. Technical Feasibility

Once a water-deficient area is identified, technical specialists conduct detailed studies to determine the optimal solutions for construction and operational efficiency. This step ensures that the proposed plants are both technically feasible and cost-effective.

3.1.3. Environmental Considerations

Environmental impact assessments are conducted in parallel with technical studies. After defining the project boundaries, environmental experts evaluate the potential impacts during various project phases. These studies help identify mitigation measures and establish an environmental monitoring program. Particular attention is given to biologically and ecologically significant sites in Morocco, which serve as critical reserves for biodiversity. Efforts are made to avoid such areas to safeguard vulnerable habitats and species.

3.1.4. Constraints from Industrial or Strategic Tourist Sites

Strategic sites, including those earmarked for aquaculture or tourism, can present challenges for desalination plant development. For instance, Aglou Beach, located about 17 km from Tiznit along the Atlantic coast [4], has been identified as a promising site for aquaculture and tourism projects. Despite its potential, plans for desalination plants in this area necessitate extensive environmental studies to assess short-, medium-, and long-term impacts on marine biodiversity and ecosystems.

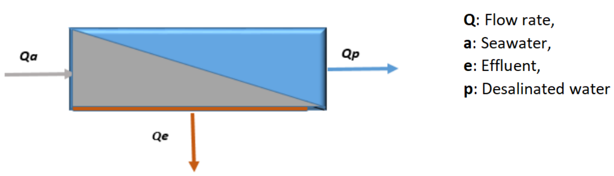
These criteria ensure that desalination plants are developed in a manner that balances water resource needs with technical, environmental, and socio-economic considerations.

3.2. Brine Discharge Salinity

The most significant component of brine is salts, such as chlorides, which, when discharged into the sea, can reach concentrations more than twice those of the receiving environment. This elevated salt concentration creates a hypersaline plume that disrupts the natural balance of the marine ecosystem.

The concentration of substances discharged by the membranes, such as salts, increases in the same proportion as the ratio between the seawater intake flow rate and the brine discharge flow rate

The calculation of the salinity of a desalination plant's effluent is based on the salinity of seawater (receiving environment) and the intake flow rate. We denote:



$$Qa = Qp + Qe \quad (1)$$

$$Sa * Qa = Sp * Qp + Se * Qe \quad \text{(Law of Mass Conservation – S : Salinity)} \quad (2)$$

The expression for calculating the conversion rate is as follows:

$$R = Qp/Qa \quad (3)$$

It can be deduced from Equations (1)–(3).

$$Se = (Sa - Sp * R)/(1 - R)$$

Where Sp ⋘ Se:

$$Se = Sa/(1 - R) \quad (4)$$

The Equation (4) can be expressed as follows:

$$Se/Sa = 1/(1 - R) \quad (5)$$

The excess salinity is as follows in Equation (6)

$$\frac{\Delta Se}{Sa} = \frac{Se - Sa}{Sa} = \frac{1}{1 - R} - 1 = \frac{R}{1 - R} \quad (6)$$

The salinity of the effluent, as well as the rate of excess salinity (the increase in effluent salinity relative to the receiving environment. $\frac{\Delta Se}{Sa}$ depends exclusively on the conversion rate selected for the membranes.

For most seawater desalination plants that handle standardized seawater quality (for example, without excess boron), where the desalination process is carried out by reverse osmosis in a single stage, the seawater, after passing through the membranes, is divided into two flows: the produced water (approximately 45% with current RO technology) and the brine discharged back into the sea (the remaining 55%).

According to the above relationship, it can be deduced that the flow discharged into the sea will be reduced by increasing the conversion rate. However, in this case, higher pressure will be applied to the membranes, causing damage and fouling, which will negatively impact both the quality and quantity of the water produced.

3.3. Techniques for Brine Discharge

The techniques used for brine discharge are numerous[13, 14], including:

- Direct discharge of brine into the sea[7] via a connection point with the land pipeline linking the desalination plant to the coast. The discharge can be gravity-fed into the sea. This method requires an environmental assessment of the discharges on marine life, as the concentrate forms a high-density plume that will touch the seabed and spread horizontally along the bathymetric slope. This hypersaline mass can negatively impact various benthic marine organisms around the discharge point. Therefore, a biodiversity study at the discharge site and the definition of potential inter-system interactions are essential[15].
- Discharge of brine into the sea via an outfall equipped with a diffuser system[7]. This technique requires three-dimensional simulation to identify the impact of increased salinity on species present in both nearby and distant fields.

- Discharge of brine into deep wells. This technique requires costly investigations to assess the impact of brine on groundwater while avoiding any type of pollution.
- Construction of evaporation ponds [16]. This technique could contribute to the eventual recovery of salts and/or exploration of certain minerals. It requires large land areas and advanced technical expertise.
- Mixing brine with treated wastewater from existing treatment plants [7]. This technique depends on the presence of nearby treatment plants to the desalination plant.

The choice between the brine discharge techniques mentioned above depends on several parameters [7], including the nature of the brine (quality and quantity), the presence of other infrastructure (treatment plants), the bathymetry of the seabed, and sea conditions (limitations of the breaking waves area).

The cost of implementing these technical solutions varies from one solution to another, with discharge of brine into the sea generally being considered the least expensive [14, 17–21].

From what has been mentioned in the **Figure 5** [22], we can deduce that discharge through a marine outfall remains an optimal solution and contributes to the preservation of marine life by projecting diffusers along the outfall to achieve brine dilution [23]. This diffuser system requires a 3D simulation study to set the salinity value that should not be exceeded.

Direct Brine Discharge		Brine Discharge through a marine outfall	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
• Lower cost: A reduced cost in the absence of maritime works • Simplicity: Easier to implement compared to systems requiring sophisticated equipment.	can present in most cases: • A negative impact on marine biodiversity, as the discharge of brine can disrupt marine ecosystems by increasing local salinity and reducing oxygen levels. • An impact on the quality of bathing waters, as an increase in salinity and turbidity in bathing areas can have harmful effects on marine organisms, thus disrupting the ecological balance and affecting the quality of bathing water. • An impact on the beach landscape, as desalination facilities can contribute to coastal erosion by altering marine currents and sand movements, and can also generate visual pollution.	Dilution of discharged brine Reducing the negative impact of increased salinity on marine species [22]	A significant cost compared to coastal discharge, this cost can be optimized by considering the length of the marine outfall and the tolerance of marine species to the salinity of the discharged brine. Indeed, a biodiversity study is required to determine the tolerance threshold of marine species present within the radius of influence of the brine.
This brine discharge technique on the coast is more cost-effective but less efficient in achieving the desired dilution. With the increase in flows produced by large desalination plants, this technique will no longer be effective.		This technique ensures the expected dilution, but it can be costly depending on the tolerances of the marine species present in the receiving environment. Indeed, the effectiveness of the marine pipeline relies on the balance of ensuring adequate dilution to prevent potential impacts on local ecosystems, which may require additional measures to minimize harm (such as extending the pipeline or adding diffusers).	
Free jet over a cliff. Example: El Hoceima desalination plant. Overflow with riprap. Example: Laayoune Desalination plant		Marine pipeline with riprap: Sidi Ifni Desalination plant under construction. All the desalination plants that are projected or under construction. Example Casablanca, Rabat, Nador desalination plants	

Figure 5. Difference between direct brine discharge disposal and brine discharge via marine outfall [22].

3.4. Technical Design Criteria for a Discharge Outfall

Desalination effluents can be 2 times more concentrated than the ambient seawater [24]; therefore, brine disposal has the potential to degrade the physical, chemical, and biological characteristics of the receiving water body [17]. To ensure that salinity does not have a harmful effect, the brine produced by desalination plants must be discharged in a way that does not increase salinity to intolerable levels.

Thus, the design of a reliable solution for the discharge of these effluents must take into account environmental and financial constraints.

To design a discharge outfall, the following steps will be undertaken:

- Define the quality and quantity of the discharge brine [25].
- Define the quality of the seawater [25], the measurements will cover the spatial distribution in the discharge area of the water's physicochemical parameters (temperature, pH, salinity, and dissolved oxygen),
- Study the marine environment, particularly through bathymetry and marine geophysics [21]. The study of the physical marine environment allows us to define the topography of the seabed on which the outfall will be placed and weighted, and to estimate the cost of maritime construction work (quantity of excavation, stability of the proposed structures, etc.)
- Oceanographic data [26]. Indeed, studies of waves, currents, and sedimentology allow us to limit the area where the waves break above which the diffusers will be projected to avoid the constraints of clogging the diffuser risers and the instability of the outfall. The diffusers improve the conditions of dispersion [21, 27] in the sea to avoid high concentrations of salinity in the water column.
  Although wave movements facilitate brine dilution into the receiving water body, they result in additional costs for operation and maintenance due to the forces generated by these waves on the outfall. It is optimal to position the discharge point away from the area where waves break and ensure sufficient water depth for effective dilution [14, 27].
- Exploration of the marine environment through a study of marine biodiversity [14].
- Identify marine protected areas
- Regulations and standards, such as the national standard NM 03-7-200 related to the monitoring of bathing water quality [28].
- Identify the impact of the desalination plant's discharges on marine and terrestrial flora and fauna, while checking the impact of the new characteristics of the plant's discharges (salinity and residual chemical reagents) [17] on the ambient environment.
- Benchmark studies on marine environment protection at the national level and studies on brine dilution at the international level.
- Geometric installation of the discharge [17].

These studies will determine the discharge point(s) and consequently the length of the outfall, the positioning of the diffusers, and the cost of the project.

3.5. Applicable Standards and Regulations in Morocco Regarding the Impact of Discharges on the Ambient Environment

In Morocco, there are environmental texts promulgated in 2003 concerning the enhancement and development of coastal resources, particularly Articles 35 and 36 of Law No. 11-03 relating to the protection and enhancement of the environment. These two articles highlight the importance of protecting marine spaces and resources [29].

Decree No. 2-04-553 of January 24, 2005, applies Articles 52 and 53 of the Water Law 10-95, the main law directly regulating the water sector in Morocco [30]. This decree addresses direct or indirect discharges, spills, and deposits in surface and groundwater that may alter the physical, thermal, chemical, biological, and bacteriological characteristics of the water. The mentioned decree does not address ambient standards (AS) and the maximum allowable modifications of water quality in the receiving bodies of water for brine discharges.

At the moment, there are no regulations limiting the physical parameters and chemical concentrations of brine effluents resulting from desalination processes in Morocco.

Actually, the preparation of regulations for effluent discharges into the ocean, as stipulated by Draft Law 81-12, should be expedited [1], especially regarding the conditions under which brine discharge permits may be refused. This draft law aims to achieve the following objectives [31]:

- The preservation of biological and ecological balances, the conservation of natural heritage, sites, and landscapes, and the fight against erosion in coastal areas.

- The fight against pollution and degradation of the coastline, regardless of its origin.

This draft law will be considered as a tool for promoting a national policy of integrated coastal management aimed at the sustainable development of coastal areas.

In the absence of a Moroccan standard specifying the limit values for discharges of effluents from desalination plants into the ambient environment, an international benchmark study is essential to establish the basic criteria for the design of discharge outfalls [32].

This benchmark study will primarily focus on international standards and best technical practices adopted by certain countries.

A large number of studies on the negative effects of brine are available [8, 13, 14, 21, 27, 33–35]. These studies show that the effects of desalination concentrate vary considerably, depending on sea conditions, the site, the biotic community at the site, the nature of the concentrate, and the extent of its dispersion. It appears that benthic populations and seagrass meadows are the most sensitive; some populations seem tolerant to high salinity effects up to 10 psu, while others are impacted by a high salinity increase of only 2–3 psu [36].

There are significant variations in regulations, but almost all share two key elements: salinity limit and compliance point expressed as a distance from the discharge point. The salinity limit is generally defined as an increase of 1 to 4 ppt (1 to 4 g l^{-1}) above ambient conditions. However, limits are also less frequently expressed as absolute salinity or as a minimum dilution level. The compliance point for the salinity limit is the boundary of the mixing zone, which is usually specified by a distance from the discharge point, ranging from 50 to 300 meters [36].

The **Table 1** shows the current brine discharge limits [35, 36].

Table 1. Brine discharge limits in many countries.

Region/Authority	Salinity Limit	Compliance Point (Relative to Discharge)
US EPA	Increment ≤4 g l^{-1} [37]	not defined
Western Australia	Increment < 5% variation from background [38]	not defined
Oakajee Port, Western Australia	Increment ≤1 g l^{-1}	not defined
Perth, Australia/Western	Increment ≤1.2 g l^{-1}	50 linear meters
Australia EPA	Increment ≤0.8 g l^{-1}	1000 linear meters
Sydney, Australia	increment ≤1 g l^{-1}	50 to 75 linear meters
Gold Coast, Australia	increment ≤2 g l^{-1}	120 linear meters
Okinawa, Japan	increment ≤1 g l^{-1}	boundary of the mixing zone
Abu Dhabi	increment ≤5 %	boundary of the mixing zone
Oman	Increment ≤2 g l^{-1} [39]	300 linear meter
Spain Spanish Mediterranean	<38.5 ppt [40]	seagrass (*Posidonia oceanica*) limit
California Environmental Protection Agency 201	increment ≤2 ppt [41]	100 linear meters
CANADA CCME	Maximum change of 10% at a water depth of approximately 30 m (not on the seabed), and with an effluent discharge velocity of approximately 3 m s^{-1}. [42]	not defined

According to this table, we can deduce:

- The standards applied at the international level are characterized by significant variation.
- The standards are set based on the tolerance of marine species in the ambient environment, as is the case for *Posidonia oceanica.*
- In Australia, the salinity limits are almost identical, but the compliance distances are different. This can be explained by the conditions of the sea state, the bathymetry of the seabed, and the depth of water sought to ensure good dilution.

4. Conclusions and Limitations

Currently, Morocco does not have regulations that restrict the physical parameters and chemical concentrations of brine discharges from desalination processes.

In Morocco, the tolerance limit for brine discharge, which is followed by most desalination plants, is set at a distance of 300 meters from the discharge point. At this distance, the salinity value must not exceed 2 parts per thousand (ppt) above the ambient environmental salinity. These values are based on the requirements of the financial donors and remain subject to revision according to the marine environment in question.

The discharge of brine via marine outfalls requires a simulation study of the discharges at sea. To achieve this, it is essential to determine the salinity limit that should not be exceeded and to delineate the area where waves break (surf area) and the zone where sediment transit occurs.

Determining these two elements helps to protect the marine species within the area impacted by the brine (increased salinity) and to safeguard the outfall against the hydrodynamic forces generated by waves.

The fundamental steps for design are outlined below:

- Define the area where waves break; this distance varies from site to site. According to marine studies conducted in the project marine area, this distance ranges from 150 to 1000 meters and may extend further. Accurate determination requires an analysis of wave and current patterns.
- Avoid the sediment transit zone; a sedimentology study is necessary to assess sediment transit and its area of dispersion.
- Conduct bathymetric and marine geophysical studies to characterize the layers and thicknesses of sediments on the seabed.
- Adhere to the minimum jet velocity threshold needed to achieve effluent dilution. Generally, optimal dilution processes in the near field are found at velocities between 2.5 and 6 m s^{-1}.
- In the absence of legally defined thresholds, acceptable impacts of brine discharges should be assessed based on their actual effects on marine life. The average salinity of Atlantic Ocean water is around 35 g/kg, with salinity varying seasonally and spatially within a range of ±2 g kg^{-1}.
  - For most marine species, lethal salinity ranges between 50 and 70 g kg^{-1}, while salinity below 40 g/kg is generally without effect.
  - For seawater with a salinity of 37 g kg^{-1} and a conversion rate of 45%, the effluent will have a salinity of 67 g kg^{-1}. Thus, the effluent discharge is a significant source of lethal contamination for most marine flora and fauna, necessitating a dilution study before discharge.

With the significant increase in planned desalination plants along the coast, it is imperative to implement legislation that sets limits on aquatic pollutant levels at the discharge point (Effluent Standards - ES) and in the receiving environment (Ambient Standards - AS).

Ambient standards necessitate evaluating the ambient response, which is often linked to the concept of a "mixing zone,"[33] a specific impact area where water quality parameters may exceed acceptable limits.

Additionally, an experimental investigation using scaled physical models must be conducted to determine the most effective brine dilution discharge systems in the near-field region[37].

The key parameters for brine discharges from desalination plants, which require rigorous monitoring, are temperature, salinity, pH, dissolved oxygen, dissolved organic matter, and residual chemical pollutants such as copper, nickel, free chlorine, and chlorinated by-products[9].

Author Contributions

Conceptualization, Z.C., and E.C.; methodology, Z.C.; validation, E.C., M.K., and A.N.; formal analysis, Z.C. and E.C.; writing—original draft preparation, Z.C.; writing—review and editing, Z.C. and E.C.; supervision, E.C., M.K. and A.N.; project administration, E.C., A.N.

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Conflicts of Interest

The authors declare no conflict of interest.

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