Regulating Desalination Brine Discharges in Morocco: A Comparative Assessment of Regulatory Framework Robustness

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Abstract. The quick expansion of seawater desalination in Morocco has turned into a major answer, somehow, to the growing water scarcity that keeps getting worse, somewhat, worsened by climate change. Still , the current national legal framework feels a bit vague not specific enough about how hypersaline brine discharges should be environmentally regulated. Because of this regulatory gap, there is real worry about the likely effects on coastal ecosystems, in practice. This study tries to check how "solid" the Moroccan rules really are, specifically for brine discharges from seawater desalination plants. To do that, the research gathers a review of Morocco's environmental legal framework, looking at Laws 36-15, 11-03, 12-03, 81-12, and 49-17, and it also examines a set of implementing decrees connected to discharges, environmental impact assessments, and environmental control, all together. On top of that, the study puts forward the C-Q-G-M analytical framework as a sort of new lens for judging regulatory robustness, based on four evaluation angles: coverage, technical quality, governance and monitoring. After that, the Moroccan framework is compared with three international benchmark cases, to see how closely it matches advanced regulatory practices. Overall, the CQ-G-M assessment indicates the Moroccan framework is only partially robust, and the most noticeable weaknesses seem to be located in the technical quality lane, not so much elsewhere. The results point toward several important regulatory and operational gaps, especially the absence of specific salinity thresholds, the missing detailed procedures for mixing zones, and unclear coordination rules across the competent agencies. Also, there is no consistent, standardized package of requirements for environmental monitoring. Also, there is no consistent, standardized set of requirements for environmental monitoring.

Keywords: Seawater desalination; Brine discharge; Regulatory framework; Morocco.

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1 Introduction

The growing scarcity of freshwater resources, exacerbated by climate change and rising demand, is leading to increasing reliance on unconventional water resources, particularly seawater desalination [1–3]. Globally, approximately 15900 desalination plants produce nearly 95 million m³/day of desalinated water and generate about 142 million m³/day of brine, a concentrate volume approximately 50% greater than desalinated water production. This massive co-production of hypersaline brine, sometimes loaded with pretreatment chemicals, is now recognized as one of the main environmental barriers to the rise of desalination.

In conventional seawater reverse osmosis processes, the recovery rate (R) is generally in the order of 40 to 50%, with an overall average value of approximately 42% for the seawater–reverse osmosis system. This limitation is mainly due to the gradual increase in the osmotic pressure of the concentrate, the risks of membrane fouling and scaling, as well as the increase in hydraulic pressure and energy consumption required for higher recovery rates [3,15–16].

The brine flow rate (Q_{brine}) is related to the feed flow rate (Q_{feed}) and the permeate flow rate (Q_{perm}) by the following equation:

$$Q_{brine} = Q_{perm}\,[(1 - R)/R] \qquad (1)$$

Thus, for a recovery rate between 40 and 50%, each cubic meter of produced water generates approximately 1,0 to 1,5 m³ of brine. This significant production of brine makes the management of brine discharge a central focus of the environmental assessment of desalination projects [3,17].

In Morocco, where the renewable water supply has increased from about 2560 m^3/capita/yr in 1960 to nearly 600 m^3/capita/yr today, well below the water stress threshold of 1000 m^3/capita/yr, desalination has become a pillar of national water security strategies [6–8]. According to Védie (2025), in line with the PNAEPI and recent national guidelines, the fixed desalination plant selected for the analysis includes 26 stations, either in operation, under construction or planned, for a combined capacity close to 1.26 billion m^3/year by 2040 [18]. This total includes 17 stations in service or under construction, representing about 322 Mm^3/year, and 9 scheduled stations, representing about 936 Mm^3/year [18]. More recent departmental data also indicate 17 existing projects, for a production capacity of 350,3 Mm/year, as well as 4 ongoing projects totaling 567 Mm/year; they also confirm the objective of mobilizing about 1,7 billion m^3/year of desalinated water by 2030 [19]. This expansion of desalinization capacity is inevitably accompanied by a rise in brine discharge volumes, especially along the Atlantic and Mediterranean shores, where the primary coastal desalination infrastructures are gathered [8,14,16,19]. From the literature, these discharges may end up producing local increases in salinity and density, change thermal gradients,and encourage the buildup of chemical substances, which could have consequences for benthic communities, seagrass meadows, and the way coastal ecosystems work or function [3,9–12]. Several case studies carried out in Morocco, mainly around the Laâyoune facility, support that receiving environments stay quite sensitive to brine plumes, and they stress how much the discharge conditions matter, as well as the shape of the coastline, like its coastal morphology.

In this context, regulatory frameworks play a key role, in defining quality standards for effluents, and receiving waters, discharge conditions too (including mixing zones and compliance points) plus monitoring requirements, and they also steer technological choices toward more sustainable options like dilution optimization or brine reuse. That said, while several advanced jurisdictions, such as Spain, California, and Australia, have already built fairly detailed frameworks that include salinity thresholds regulated mixing zones, and rigorous monitoring programs, the Moroccan framework, grounded notably in Laws No. 36-15 and No. 11-03, still looks largely generic when it comes to brine discharges. It kind of exposes a regulatory gap, with regard to thresholds, the allowed mixing zones, and even which specific monitoring requirements should be applied.

This article aims to check how robust this framework really is, using a sort of original C-Q-G-M analytical layout (Regulatory Coverage, Technical Quality, Governance, Monitoring) and then compare the Moroccan example with benchmark jurisdictions (Spain, California, Australia) , to spot the structural voids and put forward suggestions for a regulatory framework more aligned with the fast expansion of desalination and the safeguarding of marine ecosystems [1,2,5,13–14].

2 Materials and Methods

2.1 Overall Methodological Design

This study adopts a comparative qualitative method, sort of like looking at it from several angles and not only by checking formal rules. It is intended to gauge how solid Morocco's regulatory framework is when it comes to the release of saline water, by working through three levels of analysis: regulatory texts, the actual environmental assessment practices, and the relevant international standards. In a way, this design helps to fold together both the normative side and the practical operational side of the system we are looking at, without losing sight of how things are applied on the ground.

The analysis is built around three parts:

• A literature review of Morocco's regulatory set: focusing on legislation dealing with water, the environment, environmental impact assessments, and the coastline, in order to judge the degree to which these instruments address brine discharges.

• An analysis of a corpus of environmental impact assessments, or EIA: here the attention is placed on discharge characterization, dilution assumptions, mitigation measures, and the monitoring arrangements proposed for the projects.

• A comparative international benchmark: a cross-check with Spain, California, and Australia, chosen because of the maturity of their frameworks related to environmental thresholds, mixing zones, modeling, and monitoring [20–22].

The entire corpus is analyzed using a C-Q-G-M framework structured around four dimensions: regulatory coverage, technical quality, governance, and monitoring.

2.2 Development of the C-Q-G-M Analysis Framework

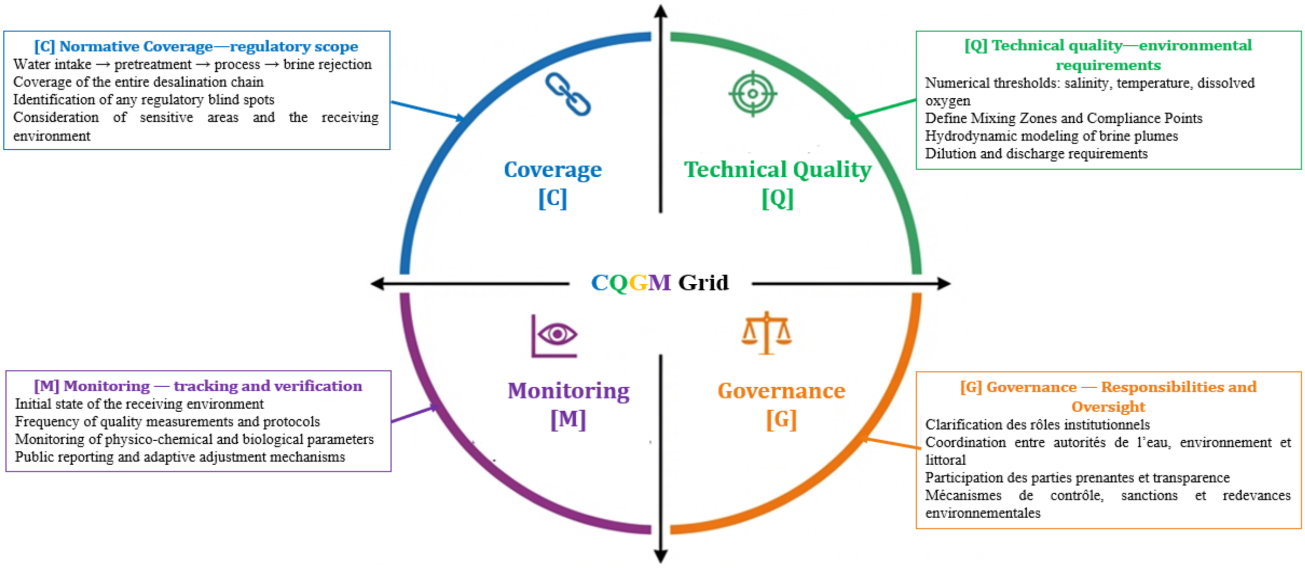


Fig. 1. C-Q-G-M analytical framework used to assess the regulatory robustness of brine discharges from desalination.

The C-Q-G-M framework was developed based on the literature on the impacts of desalination, brine management, and the governance of discharges to the sea [1,3,18,23]. As shown in Figure 1, this framework allows for the assessment of the robustness of the regulatory framework across four dimensions.

1. **Normative Coverage (C)**

This dimension assesses the existence of specific provisions governing brine discharges. In particular, it examines:

• environmental thresholds, including salinity, temperature, density, and chemicals associated with desalination;

• ecologically sensitive areas, such as seagrass beds, benthic habitats, protected areas, and zones with low hydrodynamic activity;

• mixing zones and compliance points, corresponding to areas where concentrations must comply with permissible limits after dilution.

The absence of explicit thresholds reduces regulatory control capacity and increases uncertainty in project-level environmental assessments [3,18].

2. **Technical Quality (Q)**

This dimension analyzes the technical requirements imposed on projects. It covers:

• hydrodynamic modelling: simulation of brine plume dispersion;

• design of discharge structures: diffusers, initial dilution, discharge depth, and distance from the coastline;

• conditions of the receiving environment: bathymetry, currents, stratification, and ecological sensitivity;

• best available techniques: dilution optimization, controlled co-discharge, or partial recovery.

The technical design of the discharge directly influences the extent and intensity of impacts on the marine environment [23].

3. **Governance (G)**

This dimension examines the institutional capacity to apply and control regulatory requirements. It analyses:

• the distribution of responsibilities: the roles of water, environmental, and coastal authorities, basin agencies, and operators;

• inter-institutional coordination: consistency in project review, authorization, and monitoring;

• control and sanction mechanisms: verification of compliance and corrective measures;

• participation and transparency: access to information, public consultation, and publication of results.

The regulation of brine thus depends as much on technical standards as on their institutional implementation [1].

4. **Monitoring (M)**

This dimension evaluates monitoring devices before and after the commissioning of stations. It covers:

• the initial environmental state: prior characterization of the receiving environment;

•the monitoring parameters: salinity, temperature, dissolved oxygen, chemical substances, and biological indicators;

• frequency and spatial coverage: monitoring stations, sampling intervals, and monitoring areas;

• adaptive adjustment: modification of operating conditions in the event of an observed impact.

Insufficient monitoring can lead to an underestimation of the cumulative effects of hypersaline releases [18].

Each dimension is assessed according to three levels:

• **Low:** absent, general or poorly operational dimension;

• **Medium:** dimension is present but partial, implicit, or not harmonized;

• **High:** explicit dimension, technically precise, applicable and controllable.

This scale allows for a structured comparison without numerical weighting.

2.3 Corpus of analysis – the case of Morocco

Regulatory Framework

The Moroccan corpus comprises five main texts :

• Law No. 36-15 on Water: sets forth provisions regarding resource management, discharge permits, and pollution prevention [24];

• Law No. 11-03 on the protection and development of the environment: establishes a general framework for environmental protection [25];

• Law No. 12-03 on Environnement Impact Assessments: is the foundational Moroccan legislation requiring Environmental Impact Assessments (EIAs) for public or private projects likely to have negative impacts on the environment [26];

• Law No. 81-12 on the Coastline: establishes the legal framework for the sustainable, integrated management, protection, and conservation of the coastline [27];

• Law No. 49-17 on Environmental Assessment: an updated framework for assessing the environmental impacts of projects, plans, programs, and public policies [28].

These texts are analyzed to determine whether they adequately address the specific characteristics of brines, including hypersalinity, density, dispersion behavior, effects on marine habitats, and monitoring requirements.

Environmental impact studies

A corpus of two EIA reports, related to the projects of Safi and Jorf Lasfar, is examined alongside a scientific case study on the Laâyoune plant [12,29–30]. The whole thing is considered through three criteria: document accessibility, sectoral representativeness and geographical diversity, along the Atlantic shore of Morocco. With this approach, the gap between the general regulatory framework and what happens in practice at the project level can actually be evaluated.

2.4 International benchmark

This comparative analysis focuses on three reference countries:

• **Spain**: a Mediterranean reference point, characterized by its geographical proximity and a climate similar to that of Morocco [21];

• **California**: a well-established regulatory framework, high environmental standards, and experience in monitoring [22];

• **Australia**: a context of water stress and adaptive management of coastal environments [23].

This comparison aims to identify elements that can be applied to the Moroccan context: explicit thresholds, compliance criteria, hydrodynamic modeling, biological monitoring, transparency, and adaptive adjustment.

2.5 Comparative Analysis Method

The comparative analysis is kinda grounded in a consistent way of using the C-Q-G-M framework on Moroccan documents, and also on some EIAs, and then relying on case studies as international benchmarks too, so we can see what Morocco could take as a model , for certain areas that may need inspiration. It sort of helps keep the whole process coherent, at least in theory, because we are applying the same logic throughout, no big surprises. This approach supports the formulation of operational recommendations, using verifiable criteria, and those criteria are specifically tied to the expansion of desalination in Morocco and also to the expected increase in brine discharges.

3 RESULTS

3.1 Results of the C-Q-G-M grid – Morocco

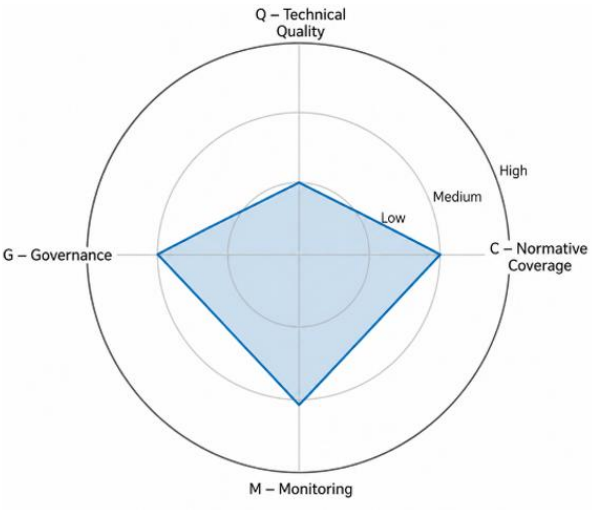
Table 1. Application of the C-Q-G-M framework to the Moroccan regulatory framework for desalination brine discharges

	Criterion	Level	Justification and identified shortcoming
C — Normative coverage	C1. Primary legislation	**Medium**	Law No. 36-15 integrates desalination into water resource planning, and Law No. 81-12 provides a framework for coastal protection. However, desalination brine is not explicitly defined as a specific legal category of discharge. [24,27]
	C2. Secondary regulatory texts	**Medium**	Decree No. 2-04-553 regulates discharges into surface and groundwater. However, no sector-specific decree dedicated to hypersaline desalination discharges has been identified. [31]

	Criterion	Level	Justification and identified shortcoming
	C3. Technical standards and limit values	**Low**	Existing limit values mainly concern conventional domestic wastewater parameters, such as BOD5, COD and suspended solids. No specific thresholds are defined for salinity, density, temperature or chemical additives associated with desalination [1,17,32].
	C4. Integration into EIA procedures	**Medium**	The EIA framework requires the assessment of environmental impacts, but brine discharges are not identified as a stand-alone category. Their consideration therefore remains indirect and project-dependent. [26,28,33-34]
Q — Technical quality	Q1. Physico-chemical thresholds	**Low**	No specific national thresholds have been identified for key brine parameters, including salinity, temperature, density, residual chlorine, antiscalants or metals [1,17,31-32].
	Q2. Plume modelling	**Medium**	EIA regulations allow impact assessment and requests for additional technical information, but they do not explicitly require hydrodynamic modelling of brine plumes. [17,26,33]
	Q3. Environmental monitoring protocols	**Medium**	Water and environmental regulations allow monitoring and reporting obligations. However, no harmonised national protocol specifically addresses the physico-chemical and biological monitoring of brine discharges. [17,24-25]
	Q4. Diffuser requirements	**Low**	No national standards were identified for diffuser design, initial dilution, discharge depth or distance from shore. These aspects are mainly addressed on a case-by-case basis in project studies. [1,17,31]
G — Institutional governance	G1. Competent authority	**Medium**	Responsibilities are shared among water, environmental and coastal authorities, basin agencies and operators. No single authority is specifically mandated to regulate brine discharges. [24,26-27,37-38]
	G2. Inter-institutional coordination	**Medium**	EIA committees and basin councils provide coordination mechanisms, but they remain general and are not specifically structured around hypersaline desalination discharges. [24,33-34]
	G3. Transparency and access to data	**Medium**	The right of access to information and environmental transparency principles exist. However, no national public register of permits, monitoring results or non-compliance records related to brine discharges has been identified. [24-25,38]
	G4. Stakeholder participation	**Medium**	Public inquiry procedures under the EIA framework allow public participation, but they are not specifically tailored to coastal stakeholders affected by brine discharges, such as fishers, residents or marine users. [34,37-38]
M — Monitoring	M1. Field inspection and control	**Medium**	The environmental police provides a legal basis for inspection and control, but no inspection mechanism specifically targeting brine discharges has been identified. [35-36,38]
	M2. Administrative and criminal sanctions	**Medium**	Environmental and coastal legislation provides sanctions for illegal or non-compliant discharges. However, this regime remains general and applies to brine discharges by extension. [25,27,35]
	M3. Complaints and third-party appeals	**Medium**	General mechanisms for appeal, administrative investigation and public participation exist. However, no specific complaint mechanism for communities affected by brine discharges has been identified. [25,34]
	M4. Periodic compliance reporting	**Medium**	Monitoring and reporting obligations may be included in permits and EIAs. However, no harmonised national reporting format specific to brine discharges exists. [24,26,28,31]

The C-Q-G-M analysis reveals that the Moroccan framework is only partially robust: while the normative, institutional, and operational dimensions can generally be addressed by extending the scope of general regulations, technical quality remains limited by the absence of specific thresholds, rules on mixing zones, modeling requirements, and specifications for discharge structures.

Figure 2 presents a radar plot summarizing the robustness levels of the four dimensions C-Q-G-M applied to Morocco's regulatory framework for desalination brine discharges.



3.2 Benchmark international

The international benchmark aims to identify the dimensions in which some countries present advanced practices that could shed light on the evolution of the Moroccan framework. Three reference cases were selected: Spain, California and Australia. These cases are distinguished by the existence of more explicit environmental and technical requirements regarding brine discharges, particularly regarding environmental assessment, salinity thresholds, mixing zones, plume modeling, diffuser design and environmental monitoring [20,22,39-44].

Table 2. International benchmark of advanced practices relevant to Moroccan brine discharge regulation.

Reference case	Strong dimensions identified	Advanced practices observed	Lessons for Morocco
Spain	Normative coverage; environmental monitoring; technical quality	Brine discharges are integrated into environmental impact assessment procedures and environmental monitoring plans, with particular attention given to the ecological sensitivity of the receiving environment, especially Posidonia oceanica seagrass meadows. Some environmental impact statements and discharge authorisations also include salinity thresholds, dilution requirements, and specific monitoring plans [20,39-41]	Explicitly integrate brine discharges into Moroccan EIAs and adapt discharge requirements to the vulnerability of sensitive coastal receiving environments.
California	Normative coverage; technical quality; governance; monitoring and control	The Desalination Provisions of the Ocean Plan provide a specific framework for the planning, permitting, operation, and monitoring of desalination facilities. They include requirements related to seawater intakes, brine discharges, marine environmental protection, salinity limits in the receiving environment, mixing zones, interinstitutional coordination, monitoring, and reporting [42].	Develop a national framework specifically dedicated to brine discharges, including thresholds, compliance points, mixing rules, modelling requirements, and monitoring obligations.
Australia	Technical quality; environmental monitoring; compliance reporting	The Australian approach combines water quality objectives, prior environmental assessment, dispersion modelling, the use of diffusers, physicochemical and biological monitoring, and environmental compliance reporting. These practices are documented in particular in the desalination projects of Perth and Victoria, while the study by Clark et al. illustrates the case of Sydney/Kurnell and the ecological effects associated with discharges and hypersaline diffusers. [22,43-44].	Develop national technical requirements for the design of discharge structures, physicochemical and biological monitoring, and environmental reporting.

3.3 Overall Comparative Analysis

The comparative analysis shows that the most useful international experiences for Morocco are not only about the existence of a general environmental framework, but above all in how brine risks get translated into operational requirements. The cases studied, you can see it , highlight several levers for improvement: legally define desalination brines, set salinity thresholds that match the receiving environments, formalize mixing zones, make hydrodynamic modeling of plumes mandatory, supervise the design of the diffusers and harmonize the environmental monitoring protocols. So , the comparative analysis confirms that the evolution of the Moroccan framework should try to move from a general discharge framework toward a more specific system , one that is technically verifiable and tuned to hypersaline discharges coming from desalination.

4 Discussion

4.1 Interpretation of the results

The application of the C-Q-G-M framework shows that Morocco's regulatory framework, for brine discharge is sorta partially robust, sort of. This situation reflects a lack of regulatory clarity regarding hypersaline brine from desalination.
The main results can be summarized as follows:

- Average regulatory coverage: the laws cited do not explicitly recognize brine as a specific category of discharge [24–28].
- Low technical quality: lack of explicit limit values for the physicochemical parameters of discharges and of operational guidelines governing the dispersion of saline plumes [17,23,31–32].
- Intermediate governance: several institutions are involved in authorization, control, and monitoring, but there is no specialized coordination mechanism for hypersaline discharges [1,37,38].
- Insufficiently standardized monitoring: environmental monitoring depends mainly on the requirements of EIAs, which leads to a variable approach from one project to another.

Thus, the main problem lies in the legal framework's limited ability to translate the specific risks associated with brine into measurable, harmonized, and verifiable technical requirements.
This limitation becomes more acute in the context of the rapid expansion of desalination in Morocco. The projected increase in desalinated water production capacity will inevitably lead to a rise in the volume of brine discharged into the sea [18,19].
An international comparison confirms this assessment. The cases of Spain, California, and Australia show that regulatory robustness depends less on the mere existence of general regulations than on the integration of operational requirements [20–22,39–44].

4.2 Environmental Implications

The regulatory gaps we've pointed out have quite a big environmental effect. Brines coming from reverse osmosis are usually very salty, and they may also carry substances that link back to membrane pretreatment or cleaning, like scale inhibitors, biocides, coagulants, residual chlorine, or just trace metals [3,17,23].

When it comes to the environmental risk, it's mainly about a few things, and yes, they can stack up:

- a local rise in salinity, can disrupt the physicochemical baseline in the receiving area, kinda like, you know, that delicate balance;
- if the discharge density is too high, the saline plume might end up settling nearer to the seafloor, especially when dispersion is not enough;
- possible impacts on benthic habitats, which are particularly reactive to shifts in salinity and dissolved oxygen [9,10,44];
- likely effects on seagrass beds, phytoplankton assemblages and the coastal food web structure [17,23];
- a gradual build up of multiple pressures, especially in coastal zones that have weak hydrodynamic activity or where there is a high concentration of infrastructure.

These risks shouldn't be viewed in isolation, they should be examined in the wider context of climate change. As sea temperatures climb, current regimes begin to shift, and the strain on conventional resources keeps growing, then the natural "dilution" capability of the receiving areas can decline. Still, brine management really needs to be handled as an environmental, regulatory and climate issue, not as something separate, just sitting there on its own.

5 Conclusion

This study shows that Morocco's current regulatory framework is not yet strong enough, to specifically deal with the brine discharge coming from desalination plants. Morocco has a fairly solid legal base, but it stays somewhat general in nature and it is still not sufficiently tailored to the physico chemical, hydrodynamic, and ecological features of these hypersaline brines.
The main shortcomings identified include:

- the lack of specific salinity thresholds;
- the inadequacy of dilution criteria and mixing zone procedures;
- insufficient requirements for hydrodynamic modeling;
- the heterogeneity of EIEs;
- the absence of standardized post-operation monitoring protocols;
- institutional coordination that still needs improvement.

The scientific contribution of this article lies in the application of the C-Q-G-M framework as a tool for assessing regulatory robustness. By distinguishing between regulatory coverage, technical quality, governance, and monitoring, this framework goes beyond a descriptive analysis of regulatory texts and identifies priority areas for improvement.
The results suggest that Morocco's regulatory framework should evolve toward more specific, operational, and integrated regulations. This evolution should support the expansion of desalination while incorporating the protection of marine environments, climate adaptation of infrastructure, and circular economy opportunities related to brine recovery. [2,4,5,13].

6 Recommendations

Based on the findings of this study, the following recommendations can be proposed:

- Develop a regulatory framework that is specific to brine discharges, in the form of a sector-specific decree or technical orders;
- Set salinity thresholds, establish dilution criteria, name compliance points, and also include rules about mixing zones;
- Standardize EIAs for desalination projects through national specifications;
- Require hydrodynamic modeling of brine plumes prior to authorization;
- Establish post-operational environmental monitoring of salinity, temperature, dissolved oxygen, chemicals, and biological indicators;
- Integrate brine recovery into a circular economy approach;
- Take climate change into account in the design, authorization, and monitoring of desalination projects.

These measures would reduce the gap between the national ambition to develop desalination and the level of environmental protection required to preserve Moroccan coastal ecosystems.

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