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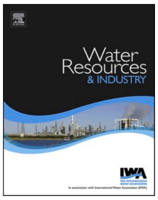

The perils of building big: Desalination sustainability and brine regulation in the Arab Gulf countries

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ABSTRACT

Seawater desalination has become an accessible option for augmenting freshwater supplies worldwide. In the countries of the Gulf Cooperation Council (GCC), it has been practiced for decades as the main source for domestic water use. Sustainable desalination requires addressing environmental impacts including damage to ecosystems from the high volumes of brine in the Gulf. This paper examines challenges related to environmental regulation of brine management in the Arab Gulf countries using the example of Qatar. It analyzes the brine challenge through infrastructure planning policies and stakeholders' perceptions. The brine issue has been identified as a major environmental concern that requires action through discharge infrastructure, brine management technologies, and regulatory approaches based on quality thresholds and monitoring systems. Although there is a high level of agreement on the solvability of the brine issue, there are limitations with regard to the high reliance on desalination rendered through large-scale infrastructure. These limitations necessitate complementary water supply infrastructure for storage or the development of other sources through water reuse and storage. While water security considerations require prioritization of protection and supply continuity through desalination, incremental change through a stepwise dual approach of brine management and regulation is still possible.

1. Introduction

Desalination is increasing around the world due to water scarcity and economic growth, and already 16,000 plants for domestic water use exist worldwide [1]. With increasing desalination, environmental concerns related to water intake, brine disposal, and greenhouse emissions are also increasing [2,3]. The impacts of brine on the receiving environments such as groundwater or marine ecosystems are becoming more evident [2,4], while technical solutions are being suggested to manage or minimize the issue [5]. The brine problem has still not been fully solved technologically, and brine regulation is unevenly implemented, with many countries lacking rules on water quality and the monitoring of brine disposal [6].

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The Persian/Arabian Gulf (hereinafter the Gulf) has the largest desalination capacity in the world, while the brine produced has had important adverse impacts on coastal ecosystems [7]. Brine volumes in the Gulf might decrease with the development of new desalination plants that rely on membranes, but this improvement will take time to materialize. Despite the wide use of thermal technologies in the Gulf, membrane-based technologies are becoming more popular in the Middle East due to their lower energy consumption, lower environmental footprint, and more flexible capacity [8]. Reverse osmosis (RO) is now the most commonly used desalination process worldwide, comprising 61 % of the global desalination capacity, followed by multi-stage flash distillation (MSF) at 26 % and multiple-effect distillation (MED) at 8 % [9]. The efficiency of RO technology has been improving, allowing it to become more widely applied around the world (Chen et al., 2016). In plants using seawater RO (SWRO), energy-recovery devices (ERDs) are a key component that has greatly helped reduce operation costs [10]. Compared to SWRO, MSF and MED systems – common technologies in the Gulf – withdraw higher volumes of seawater per cubic meter of product water for cooling and partial use as feed. They discharge larger volumes of concentrated brine at temperatures higher than that of seawater. The chemical contaminants and high temperature of the rejected brine negatively affect the marine environment. In view of this, the increased use of SWRO desalination systems is argued to result in less environmental impact in Qatar and the Gulf [11]. However, the rejected brine from SWRO is more concentrated and as such can be harmful if not disposed of properly [1,12].

In the Gulf, municipal water supply stems almost entirely from desalinated water [13]. For many policymakers, the benefits of supplying freshwater through desalination in the arid environments of the Gulf are enormous, although the brine management issue is challenging and complex to solve. However, there is a lack of knowledge on the reasons for the brine issue in the Gulf not being regulated effectively or remediated technologically. The academic literature puts forward many feasible technologies and successful brine-management cases, while the energy-rich Gulf countries theoretically have the means to address the brine issue. In this paper, we examine brine regulation policies in the Gulf using the example of Qatar and highlight the role of large-infrastructure planning in hindering the regulation of brine. Through interviews with stakeholders and the study of the specific Qatari desalination context, we show that desalination is a national security issue involving highly sensitive and centralized coastal infrastructure, and as such, addressing the environmental impacts of processed brine would require different modes of regulatory and technological experimentation based on incremental changes, long-term infrastructure integration, and ensured supply continuity.

2. Desalination as a technocratic or a national security issue?

2.1. The dominance of the managerial-technical view of desalination regulation

The brine management issue is presented in the academic literature primarily as a technical problem that can be solved through biotechnological or engineering interventions carried out at the level of the desalination plant. As a result, the bulk of research on brine management has focused on brine management technologies that are more friendly to the environment and would either decrease the discharge of toxic pollutants into the sea or recover materials from the brine [14–17]. As will be explained later, this technical view of the technological feasibility of solving the brine issue is also a dominant view among desalination practitioners and academic experts, who mostly stem from the engineering sciences. In the Gulf, for example, brine management is the subject of several experimental approaches (e.g., brine dilution, recovery of materials, the use of brine for enhancing recovery of oil and gas, etc.). These approaches have, however, not alleviated the need to impose more explicit regulations.

This notion about the “solvability” of the brine issue is contrary to the fact that the brine’s environmental impacts are still commonplace [18,19]. One explanation lies in the cost of brine mitigation technologies. For example, many of the technologies for material recovery presented in the academic literature are not economically viable [15]. The much-publicized idea of zero-liquid discharge (ZLD) can have a positive ecological footprint, but it still requires commercial development and regulation [7]. It is, rather, a final aim or a future pathway for sustainable desalination [12,20]. Even for some disposal measures such as deep-well injection, there can be significant costs as wells as environmental risks from leakage or the destruction of ecosystems [7,21]. For these reasons, water production through desalination will never be fully environmentally friendly in regions such as the Gulf, but its environmental impacts can be greatly reduced through a dual approach of applied technology and regulation [22]. Currently, there are comparatively low regulatory and enforcement levels in the Gulf [6,7], which prompts the question as to why, considering the financial power of Gulf countries, the brine problem is not more effectively regulated nor technically solved.

2.2. Towards an alternative explanation: the infrastructure security thesis

The critical literature on desalination has highlighted the misleading techno-managerial representation of desalination as a panacea for solving water supply problems at low cost [23–25]. Critical studies stress the need to consider political, legal and social explanations behind the rise of desalination as a “neoliberal” model of water control [26,27]. In the context of the Gulf, there are only a few studies that highlight non-technical aspects of desalination management. For example, Barau and Al Hosani [28] argue that the desalination industry is embedded within a context of interest-driven stakeholders involved in decisions about environmental governance. van der Merwe et al. [29] analyzed regulations and actors involved in the environmental governance of desalination in Saudi Arabia, and identified emerging regulatory frameworks and overlap of responsibilities. Al-Saidi and Saliba [30] embedded desalination activities in the Gulf within the context of mounting risks related to infrastructure planning and global as well as regional (environmental) change. They argued that highly centralized and large-scale desalination infrastructure can be more susceptible to supply-related risks in the Gulf.

In a similar vein, this paper shifts the focus to infrastructure planning and shows how the mega-infrastructure for desalination in the

Table 1

Desalination plants and centralization trends in the Gulf.

Country	Total capacity (m^3/day)[a]	Total number of plants (2017)	Example of large-scale desalination plants per country			
			Large-scale plants (year of operation)	Total approximate capacity (m^3/day)/MW	Technology	Main beneficiary cities
Bahrain	856,800	5	Al Hidd 1 (2000)	270,000/280	MSF	Several urban centers in Bahrain
Kuwait	2,835,850	10	Zour South, North (1988, 2016)	950,000/4000	MSF and RO	Several cities
			Doha East, West (1978, 1983)	970,000/3600	MSF, MSF and RO (West)	Kuwait city
Oman	1,491,639	60	Al Ghubrah (1976)	300,000/2000	MSF	Muscat, Oman
			Barka 1, 2 (2003, 2009)	300,000/400	MSF, RO (Barka 2)	Muscat, Oman
Qatar	2,066,954	10	Ras Abu Fontas A, A1, A2, A3, B, B2 (1994, 2010, 2015, 2017, 1998, 2008)	1,065,000/1500	MSF, RO (Ras Abu Fontas A3)	Doha and other cities
			Um Al Houl (2016)	620,500/2500	MSF & RO	Doha and other cities
			Ras Laffan A, B, C (2004, 2008, 2011)	740,000/4500	MSF and MED (for plant C)	Doha and industrial cities
Saudi Arabia	7,653,000	45	Jubail 1, 2 (1982, 1983)	1,150,000/2750	MSF	Riyadh
			Shoaiba 1, 2 (1989, 2001)	650,000/750	MSF	Mekkah, Taif & Jeddah
			Ras Alkhair (2014)	1,000,000/2400	MSF & RO	Ma'aden Co. (minerals company), Riyadh, Sudair, Al-Washim
			Yanbu 1, 2, RO (1981, 1998, 1998)	380,000/500	MSF, RO (Yanbu RO)	Medina
			Jeddah 3, 4 (1979, 1982)	300,000/850	MSF	Jeddah, Mekkah
UAE	7,477,781	44	Jabal Ali (1976, 2013 for M station)	2,000,000/7800	MSF	Dubai
			Fujairah, F2 (2004, 2011)	1,000,000/2760	MSF & RO	Fujairah, Sharijah and Abu Dhabi
			Umm AlQuwain (to be finished by 2022)	682,900	RO	Ras Al Khaimah
			Taweelah (under initial phase of construction)	910,000	RO	

[a] Data for the year 2018 for all countries except for Bahrain (2017).

Sources: For the number of plants and total capacity, GCC stats at https://dp.gccstat.org/; for information on the plants, Al-Saidi and Saliba [30], Fanack Water: https://water.fanack.com/, and official websites of plant operators.

Gulf can pose limits and conditions on the management of the desalination brine. Using the perceptions of involved stakeholders and experts along with comparative data, we illustrate why desalination has been a matter of national security in the Gulf. Desalinated water is not just one option for domestic water supply; it is the only option in many countries of the Gulf Cooperation Council (GCC). While other countries might have hundreds of desalination plants and multiple supply alternatives, many GCC cities depend entirely on one or few large-scale desalination plants (see Section 3.1). With yet limited storage and contingency options, environmental governance in the GCC might prefer a precautionary approach towards changes in desalination operations, thus effecting the scope of regulatory and technological interventions in the management of the brine. Such a precautionary approach can have important implications for how we understand environmental externalities and evaluate brine management remedies.

3. Case study

3.1. Centralization and desalination mega-infrastructure in the Gulf

Although most of the world's ca. 16,000 plants are located across different regions in the United States, China, Australia, Europe, and the Middle East, the bulk of the global desalination capacity is concentrated in one area, namely the Middle East and North African (MENA) region, which accounts for around half of the global capacity of ca. 95 million cubic meters per day [1]. The GCC region stands out for its large capacity that is delivered through relatively centralized infrastructure. Table 1 shows some large desalination plants in the GCC to indicate this centralization trend. For example, ca. 50 % of the desalination capacity in Saudi Arabia is provided by five plants (i.e., sites with different desalination stations), while 60 % of the UAE's capacity is delivered through four plants. In fact, eight of the ten world's largest desalination plants in 2021 were in the GCC region, with the remaining two in Israel. In comparison, Spain had ca. 950 plants in 2005 producing around 1.5 million cubic meter per day [31]. There are also other cases of high centralization in desalination production. For example, Israel currently produces ca. 2.18 million cubic meters per day from five plants, while Singapore opened its fifth desalination plant in 2022 with a total capacity of ca. 0.89 million cubic meters per day. As will be argued in this paper, the specific context of the GCC region in terms of highly centralized desalination infrastructure and the lack of alternative supply options can limit regulatory solutions to environmental issues such as brine management.

3.2. The case of the brine management

Produced brine is one of the most concerning environmental impacts of desalination activities in the Gulf. Although the Gulf is responsible for half of global desalination capacity, it produces ca. 70 % of the brine globally [1]. The discharge of the brine is

Table 2
Overview of desalination plants and ownership structure in Qatar.

Desalination plant	Approximate capacity per plant in m^3/day (power capacity)	Technology	Ownership
Ras Abu Fontas (RAF) A (1994)	250,000	MSF	100 % Qatar Electricity and Water Company (QEWC)
RAF A1 (2010)	204,545	MSF	
RAF A2 (2015)	163,659	MSF	
RAF A3 (2017)	163,659	RO	
RAF B (1977–1998)	150,000 (609 MW)	MSF	
RAF B1 (power generation only)	376 MW	MSF	
RAF B2 (2008)	131,818 (567 MW)	MSF	
Dukhan (1997)	9092	MEF	
Abu Samra (1982)	909	RO	
Qaeedat al-Shamal (1993)	909	MSF	
Um al Houl (2016)	620,000 (2500 MW)	MSF (345,502) & RO (272,762)	Umm Al Houl Power, a joint venture between QEWC (60 %), the foreign company K1 (30 %) (a joint venture between two Japanese investors, Mitsubishi Corporation (20 %) and Jera (10 %)); Qatar Foundation (5 %); and Qatar Petroleum (QP) – now QatarEnergy (5 %)
Ras Laffan A (2004)	181,818 (756 MW)	MSF	The RasLaffan Power Company Limited (RLPC), the first IWPP in Qatar. Until 2010, RLP was a joint venture as follows: AES Corporation (USA) with 55 % of shares, Qatar Electricity and Water Co. (QEWC) (25 %), Qatar Petroleum (QP) (10 %), Gulf Investment Corporation (GIC) of Kuwait (10 %). In 2010, QEWC acquired the shares of AES Corporation, thus increasing its ownership to 80 %.
Ras Laffan B (2008)	272,727 (1025 MW)	MSF	QPOWER as a joint stock company with the following shareholders: Qatar Electricity & Water Company QSC (55 %); GDF SUEZ Energy International (40 %); and Chubu Electric Power from Japan 5 %
Ras Laffan C (Ras Girtas) (2011)	286,364 (2730 MW)	MEF	Ras Girtas Power Company, a joint stock corporation owned by QEWC (45 %), Qatar Petroleum (15 %), GDF Suez (through International Power) (20 %), Mitsui & Co. (10 %), Chubu Electric Power (5 %), and Shikoku Electric Power Company (5 %).

considered a threat to the receiving environment depending on factors such as the salinity, turbidity, temperature, and chemical as well as metal contents [3]. In the Gulf, brine discharge is a regional-scale problem, since, combined with climatic change, it can affect the temperature and salinity of the Gulf as well as the health of the coastal ecosystems [7]. One reason for the high relevance of brine management in the Gulf is the deployment of thermal desalination technologies – due to the high salinity and technological accessibility among others – with low recovery ratios. For example, the desalination industry in the MENA region operates at a recovery ratio of 0.25 (i.e. 75 % as brine), while the MENA region produces ca. 70 % of the global brine load − compared to ca. 4 % in North America, 6 % in Europe, and 10 % in East Asia and the Pacific [1]. Regionally, Israel has a much higher recovery ratio due to better technologies (SWRO desalination) and brine management infrastructure [32].

Regarding the environmental impacts of the brine discharge in the Gulf, previous studies indicate a wide range of issues. Desalination process produces brine with high salinity, which can exceed seawater ambient temperature by 1.37–1.82 times. The brine contains chemicals like chlorine, coagulants, acids, antiscalants, heavy metals, and anti-foaming agents, which are toxic pollutants once discharged into the sea. It is also highly alkaline due to calcium carbonates and sulfates, affecting the physiochemical and biological parameters of the sea [33]. Heavy metals and toxic compounds can be harmful to marine creatures, degrading water quality and local hydrography, interfering with physiological processes and increasing susceptibility to diseases [18]. Vulnerability of marine organisms to salinity changes depends on their ability to regulate osmotic pressure and mobility [34]. Mobile marine organisms can regulate salt content, while slender organisms like corals and plants are more susceptible. Disposing desalination brine without dilution can cause the brine to descend to the sea floor, forming a stratified system that harms benthic organisms [18]. The toxicity of chemicals and metals increases as temperature rises, and the discharge of brine with a temperature 30–40 °C higher than incoming seawater can have various consequences on marine life. Aquatic organism growth is inhibited by high salinity and warmth [35]. Plankton, bacteria, and benthic species are among the marine animals impacted by rising salinities [36]. Further research has demonstrated that the osmotic balance is disturbed in aquatic environments when salinity levels are raised slightly above ambient levels, affecting certain marine creatures' regulatory capacities, which can lead to dehydration and, ultimately, mortality [37,38]. Furthermore, raising the temperature of saltwater makes some chemicals and metals more poisonous, negatively impacting aquatic life [39]. Given the significance of seagrass ecosystems, which are home to a variety of creatures and are subject to changes in environmental circumstances, research has concentrated on seagrasses [40].

Alongside the reliance on desalination through brine-intensive technologies, this paper has already covered the comparatively low levels of environmental regulation as a concerning issue. However, the brine issue can be mitigated through technologies and brine discharge infrastructure, which are largely used in newer desalination plants. Furthermore, newer plants often use RO technologies with comparatively less brine discharge. Table 2 lists desalination plants and their ownership structure in Qatar, showing a trend of the increased deployment of joint venture companies (JVCs) through public-private partnerships (PPP) in newer projects. While it will be argued in this paper that ownership is less important in brine mitigation, the ability to control the brine issue is particularly difficult in older plants, especially in the context of the Gulf (i.e., a high reliance on desalination for domestic water supplies and the centralization of infrastructure).

4. Methodology

The aim of this paper is to examine the environmental regulation of desalination with a particular focus on the brine issue. We apply qualitative research through stakeholders' interviews and the study of the desalination industry in Qatar. Firstly, to aid in the understanding of the current situation in the Arabian Gulf, especially the Qatari perspective (Section 5.1), some qualitative interviews were organized with representatives from research institutions (6 stakeholders) and the industry (1 stakeholder) – all from Qatar. These interviews were used to collect data on the understanding of experts and practitioners regarding the desalination brine. Initially, the interview guideline included questions on the current impacts of the brine on the Arabian Gulf ecosystems and biodiversity (see Annex 1a). Later questions were focused on potential best practices in the Qatari water sector regarding brine mitigation and regulations. The experts were also asked about barriers regarding the implementation of thresholds or new technologies, as well as their opinions on brine practices in new desalination plants and any regulatory needs in Qatar or the Gulf.

Secondly, for contextualization of the Qatari case within an international context of desalination infrastructure planning (Section 5.2), interviews with academics working on desalination issues in non-Qatari areas were conducted (4 experts). In these open-ended interviews, two issues were probed. Initially, questions were asked regarding the relevance of brine management in the non-Qatari desalination cases (see Annex 1b). Later, the experience of the experts was gauged with regard to the role of desalination within water security in the respective cases. Here, several specific issues were examined such as any experiences with security procedures during visits to desalination plants, opinions on the reliance on a certain number of plants, the share of desalination in total water use, and consequences of shutdowns of plants for water availability. In addition to interviews, data on the Qatari case were analyzed from policy documents (e.g., regarding stakeholders' responsibilities), publicly available data (e.g., on desalination plants, capacities and ownership structure), and the academic literature (e.g., for the contextualization of stakeholders' opinions and brine mitigation options).

5. Results

5.1. Brine management in Qatar: practice and perception

5.1.1. Problem perception: from discrepancies to consensus for action

The perception of the magnitude of the brine problem varies among interviewed academic experts and industry representatives. All the academics believed that brine disposal adversely impacts the marine ecosystem, mainly gauged by the parameters of salinity, turbidity, temperature and chemical contents. In contrast, a smaller number of interviewees seem to minimize the impact, citing the regenerative capacity of the Gulf ecosystem. According to one industry representative, the entire water body of the Gulf is exchanged every 6 months. This is in contrast to academic experts who mentioned major future risks including doom-laden scenarios of the Gulf becoming a second Dead Sea, or the accumulation of the harmful algae blooms (HABs) caused by the chlorine from desalination plants eventually shutting down the desalination plants.

While interviewees might perceive the scale of the brine problem differently, they agree on the necessity of seawater desalination and the need for enhanced treatment of brine. Academic experts also stress the need for more effective regulation and criticize the fact that environmental impacts seem to be less important for the industry than the energy consumption of desalination. All the interviewees mentioned that the treatment of brine needs to advance beyond the current practice of diluting it, for example, with cooling water from nearby power plants. The treatment method will need to correspond to the desalination technique, for instance, considering the amount of chemicals used in each desalination method. Several possible directions for brine treatment interventions were mentioned at different levels of technological sophistication. For example, the deployment of more efficient membranes, minerals recovery, brine concentrators, brine injection for algae production or even zero liquid discharge (ZLD) were mentioned as pathways being experimented with or assessed by the desalination industry in Qatar.

Table 3 shows the main stakeholders involved in brine impact mitigation in Qatar based on a study of relevant laws and information from interviews. This summary shows that several regulatory and coordination tasks are distributed across different stakeholders, with no unique regulatory or coordinating agency for brine management.

5.1.2. Unsolved despite capacity: limiting factors for brine impact mitigation

In the absence of clear thresholds for key brine parameters, the current practice of brine mitigation in Qatar depends on the set-up of the desalination plants. Newer hybrid desalination plants such as Umm Al Houl are constructed in a way that simplifies brine management. The high-salinity effluent from SWRO is diluted with lower-salinity brine from other desalination technologies such as MSF. The effluent may also be diluted by using cooling water from power plants. The brine at Umm Al Houl power plant is discharged into the Gulf through a 2.6 km-long pipe, which has several outlets in order to help further dilution. Continuous online discharge monitoring systems are installed at the outfall sea pit to measure various parameters. Residual chlorine and temperature are measured prior to discharge to monitor compliance with existing Qatari regulations, with the aim of achieving a zero-chlorine residue in the brine disposal product.

It is worth mentioning that newer desalination plants are built on the PPP model. However, the interviewees had split opinions as to whether this PPP model is able to improve brine management. Industry stakeholders saw the government as the only actor with sufficient funds to solve brine mitigation problems in large-scale desalination projects, while other stakeholders observed that ownership does not matter in the presence of strong regulations.

In terms of main barriers to sustainable brine management in Qatar, most interviewees mentioned the requirements of a larger area, the higher cost, and the so-far limited reusability of the brine. They also stressed the need for stronger public engagement and incentives through subsidization, since desalination technology is usually expensive. Another related factor is the energy requirement for desalination and prospectively brine treatment, which can be mitigated through the use of renewables. In this context, a new solar farm

Table 3
Stakeholders in brine management in Qatar.

Management role	Stakeholder	Tasks
Production	Qatar Electricity and Water Company (QEWC)	Management and acquisition of power generation and water desalination capacity
Production	Private companies	Independent providers of desalinated water and power through PPPs with QEWC and other public companies
Supply & distribution	Kahramma	Acting as the distributor of water and electricity and the single buyer or bulk purchaser from QEWC or the associated joint futures
Regulation	Ministry of Environment and Climate Change (MOECC)	Setting up criteria and monitoring environmental impact assessment; so far no threshold regulation for brine disposal
	Kahramaa	Setting up quality standards for desalinated water – safe drinking water with no risk to public health,
Policymaking, monitoring and coordination	Ministry of Environment and Climate Change (MOECC)	Coordination with SCENR; monitoring of environmental pollution
	Supreme Council of Environment and Natural Reserves (SCENR)	Established by Decree Law No. 11 of 2000 to set the general policies for protection of the environment and achieve sustainable development and prepare draft legislation, bylaws, decisions, and regulations
	Kahramma	Monitoring and assessment of the water supply sector's performance

for a solar desalination system is currently under consideration in Qatar.

The above-mentioned desalination mitigation barriers are in line with issues reported elsewhere in the desalination literature. However, one would expect the cost consideration to be less of an issue for the highly subsidized desalination sector in the wealthy state of Qatar. Even with strong public engagement, most experts agree that the transition towards sustainable brine management would require time for site selection for brine disposal, experimentation with recovery, and adjustments to the production processes.

Stakeholders also saw the existing environmental laws in Qatar as a limiting factor for better brine regulation since they do not directly address the brine issue. Law No. 30 of 2002 establishes environmental protection rules over 80 articles but does not specifically address brine management. Article 42 addresses the protection of the environment from pollution with the aim of applying "preventive and precautionary approaches to protect the state coasts and ports from all types, forms and sources of pollution risks" and to "mitigate and decrease the minimum possible effects". In addition, Article 55 also refers to Decree No. 55 of 1992 on the Protocol of Marine Environment Protection from Land-Based Sources and addresses the issue of effluents being discharged into the marine environment – though with no explicit reference to brine.

Another factor in need of enhancement is regional cooperation through knowledge-sharing on regional best practices. Regarding best practices, Kuwait, for example, dealt with brine management differently through the Kuwait Environment Public Authority (KEPA) by integrating the brine issue into the regulation framework and setting limits for specific parameters such as salinity. Similarly, the Emirate of Abu Dhabi (EAD) has issued a technical guidance document for handling of brine from desalination units with the aim of promoting and increasing awareness among different stakeholder of issues related to correct and appropriate brine management.

5.1.3. Potential directions for threshold-based brine regulation

As of now, there are no existing thresholds for brine management parameters in Qatar. Table 4 provides a general overview of seawater desalination regulations in the GCC region, highlighting the general lack of brine-specific measures. Overall, environmental regulations in the region suffer from legal uncertainty and fragmentated regulations. The general approach is to require an environmental impact assessment (EIA) for new desalination projects, although the requirements for such EIAs vary widely, and are not clearly stipulated by environmental laws and their bylaws. Not all GCC states have environmental monitoring plans (EMPs), which represent a key element of environmental regulations on desalination. EMPs should address issues such as site selection, mitigation of ecological impacts during construction, procedures for monitoring and contingency measures [41]. Besides, EIAs and EMPs in GCC states tend to have fewer requirements in comparison to other countries [6]. Often, these requirements depend on specific desalination projects and the environmental agency regulating the approval of new projects.

In this section, it is worthwhile reflecting on some experiences regarding threshold regulations reported by experts from forerunner countries such as Spain or Australia, or regional benchmarks such as Kuwait. With regard to salinity, thresholds exist in Spain, Australia [48] and Kuwait [18]. In Spain, the seagrass meadows of Posidonia oceanica and Cymodocea nodosa are especially vulnerable to changes in salinity. These meadows are the basis for their own marine ecosystem and their salinity thresholds are well known, so the Spanish threshold was set at 38.5 psμ [48]. However, these thresholds cannot be applied in Qatar due to the high salinity of the Arabian Gulf compared to the Mediterranean Sea. Only three endemic seagrass species can resist these extreme environmental conditions: Halodule uninervis, Halophila stipulacea, and Halophila ovalis [49], with a habitable salinity between 20 and 45 psμ (H. uninervis), or 25 and 44 psμ (H. ovalis). Although these sea grasses are halophytes, several studies from other seagrass species show the toxic impact of increased salinity, ranging from declining growth and weakening photosynthesis to increased necrosis and mortality [18]. Other organisms have deviating tolerance ranges, such as diatoms (20–75) psu, oysters (24–50), shrimps (15–40), turtles (5–48), fishes (30–50), and sharks (33–50) psu [50]. These values show that a salinity value of 50 psμ or higher would limit many species' viability, but values below 50 would relieve the associated stresses.

Table 4
Seawater brine regulation in the GCC countries.

Country	Environmental Impact Assessments (EIAs)	Environmental Monitoring Plans (EMPs)	Evidence of Quality Thresholds
Bahrain	Not clear whether EIAs are consistently used	No evidence of mandated use of EMPs	No
Kuwait	Generally required	No evidence of mandated EMPs, but monitoring of activities and environmental auditing by consultancy firms required by Law No. 24 of 2014	A salinity threshold of 42 psμ established by Kuwait Environment Public Authority
Oman	Required for certain cases	Environmental management plans required with a proposal for a monitoring program	No
Qatar	Generally required	EMPs required for the approval of new desalination projects	No
Saudi Arabia	Generally required	EMPs required but not consistently applied or used	No
UAE	Generally required	EMPs required in some cases; an operation environmental management plan required by the Environmental Agency in the Abu Dhabi Emirate; an environmental management plan and a monitoring plan required by the Emirate of Dubai	No

Sources: Bahrain: Al-Zubari et al. [42],Kingdom of Bahrain [43]; Kuwait: State of Kuwait [44], [18]; Oman: Sultanate of Oman [45]; Sola et al. [6]; Qatar: This paper's research; Saudi Arabia: Sola et al. [6], van der Merwe et al. [29]; UAE: Sola et al. [6]; Sola et al. [6], Dubai Municipality [46], Environment Agency Abu Dhabi [47].

For a threshold, it has to be considered that the salinity in the Gulf depends on the season and location: Values of 39.5 psμ in summer and 43 psμ in winter, 33 psμ at the meeting of the Euphrates and the Tigris, and 43 psμ at the southern banks occur [51]. For this reason, a salinity threshold of 42 psμ, for example as used by the KEPA [18], is not applicable for Qatar as there might already be natural conditions of 42 psμ. An Australian approach is a threshold as an absolute increase of 1 psμ above the natural salinity at a predetermined distance from the discharge point, since this can be easily monitored and compared with background salinity and annual salinity records [48]. To summarize, the Qatari authorities might consider local and temporal salinity variabilities – e.g., the Australian approach – to set up a salinity threshold between 45 and 50 psμ. More research on marine life and the flow behavior of the brine is needed in order to set a more precise value.

With regard to seawater temperature, in 2013, 73 % of the desalinated water in Qatar was produced by MSF and 18 % by MED, a total of 91 % through thermal desalination methods. The remaining 9 % is produced by RO [52]. In 2017, a new reverse osmosis plant was opened, but most water is still desalinated through thermal plants. The discharged brine from thermal desalination heavily influences the marine ecosystem because of its high temperatures. Studies reveal different values:

- Brine is 5–15 °C warmer than seawater [2,53].
- Water temperatures range from 25 to 40 °C [2].
- Water temperatures are 1.37–1.82 times higher than the ambient water temperature of 22 °C [17].

Due to the heating of the water, the amount of dissolved oxygen decreases. As a result, together with increased salinity, more species die due to thermal shocks [2]. Moreover, warmer brine increases the toxicity of metals and chemicals [17]. Setting up a threshold for increased water temperature is relatively uncomplicated because the maximum habitable temperature of all local species such as diatoms, seagrass, shrimps, turtles, fishes, and sharks is 36–37 °C [50]. However, as this temperature will very often be exceeded, a dynamic threshold is required that allows temporary temperatures slightly higher than 37 °C.

With regard to chemicals and heavy metals, the following substances are widely applied in the desalination process:

- Coagulants and flocculants are added to let substances floc to extract them more easily.
- Biocides are used to control biofouling. However, more stainless steel is used in thermal plants (the majority of plants in Qatar) than in RO plants. This reduces the number of corrosion inhibitors, since corrosion is more relevant for the aged thermal desalination plants in the Gulf than in the new RO plants [54].
- Strong acids or bases are added to adjust the pH.
- Antiscalants increase the solubility of sparingly soluble salts. They are more commonly used in RO plants to make the water more permeable [17].
- Heavy metals such as copper, iron, aluminum or nickel are used in parts or as alloys in the plants, which then become corroded, mainly due to the high temperatures used in thermal-based technologies [17].

Although the intensity of their impact varies by substance, organism and location, the main effects of chemicals and heavy metals are twofold: Firstly, they increase the water turbidity, which lets less light penetrate through the water, which again weakens the biological activity and the photosynthesis; and secondly, organisms change their metabolism or growth pattern or are even killed by them [2].

Setting up thresholds for chemicals and heavy metals takes much more effort than for increased salinity and temperature because thresholds of the species' tolerance are not as straightforward as they are for salinity and temperature. There is little quantitative data available about the amount of discharged chemicals or heavy metals. Moreover, it is unknown how the substances dilute and flow in the Arabian Gulf. Alshahri [55] measured high concentrations of heavy metals in beach sand, 500–1500 m away from a desalination plant in Saudi Arabia. After comparing it with other studies in the Arabian Gulf, he realized that his values were 10–100 times higher and concluded that these levels were associated with the fluid waste discharges from the desalination plant. One reference would be the drinking water standards of the World Health Organization (WHO), a widely known and often-referenced source in terms of water quality. Although it sets thresholds for drinking water standards, the substances affect humans in more or less the same way as they affect animals or plants, so a comparison of the measured values and the WHO values is laid out in Table 5.

It is notable that only the value of chlorine complies with the WHO guideline, whereas strong acids or bases exceed it more than a thousand fold. In the case of heavy metal values, it needs to be considered that substances accumulate in the sand, but the values are

Table 5
Comparison of observed values with drinking water standards from the WHO [56].

	Coagulants/ flocculants	Antiscalants	Biocides (chlorine)	Strong acids or bases	Iron	Aluminum	Copper	Nickel
Units	mg/L water					Mean mg/kg sand		
Observed	1–15	2–5	1–5[a]	40–50	48	27	847	4.9
Source	Panagopoulos, Haralambous and Loizidou [17]					Alshahri [55]		
WHO (mg/L water)	No guideline		5	0.02–0.2	No guideline	0.2	2	0.07

[a] In 30–120 min every 1–5 days.

still critical. In summary, due to the complexity of the different substances and the primary data source, it is difficult to set up thresholds or link all the substances to desalination activities. However, even if not all substances originate from the desalination plants, a thresholds-based regulation of brine management can protect the marine ecosystem and the local population from noxious substances.

Once thresholds are defined, appropriate sensors need to be installed, while the thresholds should be reflected in binding regulations and controlled by a designated authority, for example the MOECC or an independent environmental protection agency. At the same time, thresholds-based regulation needs to determine which measures are to be taken after the exceedance of a threshold. In Spain, for example, after exceeding the threshold, production has to be reduced by 15 % or dilution increased to a ratio above 1:2 (1 L effluent per 2 L seawater). If the salinity is still higher than the thresholds after one week, the production is further reduced by 15 %, and this continues for one month until the values are below the thresholds. Production in the plants can be stopped entirely if the values do not decrease [48]. However, as will be explained in the following sections, there are limitations to such a thresholds-based regulation or any technological updates that can affect supply continuity in the context of Qatar.

5.2. *Contextualization within water supply security: evidence and contextualization*

5.2.1. *Supply security and securitization: internal evidence*

This paper has sought to aid in understanding the directions and limitations of a regulatory approach towards brine management in Qatar. The interviews with local stakeholders have shown a consensus on the essential need for desalinated water in order to meet the needs of the local population, but also on the relevance of the brine issue in the Qatari context. Firstly, the inevitability of seawater desalination poses some limitations to any potential supply interruption. Qatar has no internal water resources to rely on as it is hyper-arid with annual precipitation of less than 100 mm [57]. In fact, its evaporation rate is 30 times more than the precipitation rate, and therefore it entirely relies on desalination for meeting its municipal water needs [58]. At the same time, the limited groundwater resources are being depleted – mainly for local agriculture – as the groundwater abstraction rate is several times higher than the corresponding recharge rate [11]. In addition, Qatar – as is the case in other Gulf countries – has witnessed a high rate of population and economic growth in the last few decades, and therefore the continuity of water supply provision for municipal and industrial uses through desalination is of national importance [30]. The use of wastewater is emerging, but it is currently limited to fodder production, landscape irrigation and managed aquifer [57]. Another factor to be considered in tackling the brine issue is the high consumption rate. On average, per capita water consumption in Qatar is relatively high – e.g., up to 1200 L per day per capita for Qataris and 150 for expats [59]. This shows the high demand and the pressure that is put on the water sector to maintain high production rates. As a result, the provision of reliable water supplies through desalination has always featured highly in national developmental discourses in Qatar. This is similar to the case of other Gulf countries, where the ability to provide desalinated water has historically been seen as an instrument of the ruling elites to increase power, distribute benefits, and acquire legitimacy [60].

Secondly, tackling the environmental impacts of desalination such as the brine produced was considered by interviewed stakeholders to be highly relevant in the context of Qatar in terms of the importance and vulnerability of affected ecosystems. The brine impacts mainly coastal ecosystems that are already under pressure from development, land-based pollution, temperature increase related to climatic change, and the overall trend of increasing salinity in the Gulf [61,62]. As its society is historically based on fishing and pearl-diving, these coastal ecosystems are highly relevant for cultural heritage in Qatar, which represents a cornerstone of its national developmental strategies; for example, the social development pillar of Qatar's National Vision 2030, which focuses on cultural identity and heritage. As a consequence, preserving coastal ecosystems and moving towards sustainable desalination is arguably of national interest in environmental policy-making.

5.2.2. *Explanation and context: external perception*

Using expert interviews and academic literature on other desalination cases, we have sought in this paper to contextualize the Qatari case of high reliance on desalination and high relevance of brine management from an international perspective. Some clear distinctions emerged that can hinder a quick regulatory fix to the brine issue. Firstly, brine management seems to have less prominence in the desalination industry of other countries such as Spain, California, Israel and Singapore than it does in Qatar. There are numerous explanations for this discrepancy. As earlier explained, the Middle East produces larger amounts of brine in comparison to desalinated water volumes; for example, Qatar holds 2 % of the world's desalination capacity but is responsible for 5 % of its brine production [1]. Moreover, other countries avail of ocean desalination or desalination into larger seas (e.g., the Mediterranean), whereas Qatar's brine ends up in the semi-closed Gulf, which is already suffering from a cascade of environmental concerns.

Secondly, it has become clear that Qatar has a higher reliance on desalination for domestic water supplies than other countries. Due to factors such as the lack of internal water resources, declining groundwater resources, and the relatively high consumption and growth rates relative to groundwater resources, Qatar is left with only desalination as a potable water source. In other cases such as Spain, desalination is only one complementary option for water supply delivered through a much larger number of desalination plants [31]. Although many of the small-scale plants are used for agriculture, the domestic water supply in Spain is supplied by both surface water and desalination. In California, desalination is emerging as a strategy for supply diversification through multiple decentralized water sources [63]. Only in Israel and Singapore is desalination highly centralized, although Singapore only depends on desalination for a smaller portion of its water supply (25 %), the remaining portions stemming from water reclamation and reuse (40 %), water transfers, or local catchments [64]. Israel has complemented its centralized desalination system (using the less brine-intensive RO technology) through some technical fixes including brine mitigation technologies and infrastructure for brine transport, irrigation efficiency, groundwater aquifer recharge (e.g., through surplus desalinated seawater) and water reuse [25,65,66].

As mentioned earlier, alternative water supply options in Qatar are limited since water reuse and aquifer recharge technologies are only yet emerging. All of this can explain why supply interruptions (e.g., in case of accidents or voluntarily to update technologies for brine management or otherwise) to the large-scale desalination plants are unworkable. Qatar's national storage project aims to build 40 mega-reservoirs for ca. 17 million cubic meters by 2036 in order to be able to react to supply interruptions [57]. Until such storage and other options fully materialize, Qatar's desalination activities remain a national security matter, and therefore desalination supply infrastructure is highly protected – such as through access restrictions or specialized security forces. For example, according to our interviews with international desalination experts, procedures for visiting desalination plants (e.g., for study trips) seem much less restrictive in other cases than in the case of Qatar in terms of feasibility or the time needed for acquiring permits.

6. Discussion and conclusions: implications for brine management and water infrastructure

As a major environmental impact with strong relevance for the Arab Gulf countries, solving the desalination brine issue requires a broad analysis beyond technological mitigation and recovery options. This paper has sought to examine brine regulation policies and their limitations in the case of Qatar. Three main insights into regulatory problem-solving challenges can be summarized. First, there is relative agreement in the perception of desalination stakeholders on the existence of barriers to solving the brine issue. Most of these barriers are related to the cost of technological interventions in desalination plants, requirements for infrastructure and land, or the limited reusability of the brine. This is consistent with the academic literature outlining the environmental trade-offs of desalination [2,18,19], or the current technological and financial limitations of brine mitigation technologies [3,5,15]. While stakeholders diverge on the existing trade-offs of desalination, they agree on the necessity of the desalination option in the absence of natural water sources in Qatar and the majority of the Gulf states. This might be a different to other countries in which the choice for desalination has been criticized for being a techno-triumphalist decision or a technical fix that favors certain political and economic interests [24,63,67].

Secondly, despite the notion of the challenges of brine mitigation, there is overall optimism about the solvability of this issue. For example, in newer desalination plants, the brine problem is perceived to be smaller than in older ones due to better infrastructure for brine dilution. Furthermore, stronger environmental regulations through designing and enforcing better water quality thresholds and monitoring systems are seen as a viable option – although it takes time to determine locally appropriate thresholds. The optimism about the availability of sufficient technological and regulatory options for addressing the brine issue contradicts the current reality, namely the lack of an effective solution for this brine issue in Qatar. This is a common reality for all Gulf countries, where the dual approach of regulation and technology has not been adopted and the region has lagged behind internationally in terms of regulatory levels [6,7,22]. Thirdly, and consequently, understanding the contradiction between the technical feasibility of problem-solving and the reality can only be resolved through an understanding of the water security context of the Arab Gulf countries. The context involves the high reliance on desalination, the lack of alternative freshwater sources, underdeveloped water reuse options, and the need for continuous operation of large-scale desalination plants to satisfy high water consumption rates. Together, insights from this research have identified several practical implications that can be summarized as follows:

- **Centralization and mega-infrastructure:** With a high reliance on desalination supply delivered through centralized and large-scale plants, complementary infrastructure for increasing the resilience of this supply is necessary, i.e., large-scale infrastructure for storage, reuse, transport and/or recharge. Until this development is completed, it is difficult to regulate water supply in any way that does not threaten supply continuity. The Gulf and other Middle Eastern countries might have already begun to acknowledge this notion as evident by the ongoing construction of large-scale storage, reuse and recharge infrastructure in countries such as Qatar or the UAE [57,68]. The need for complementary infrastructure to large-scale desalination means that the brine management issue can only be talked on the long run. Future studies might explore the complementarity between different components of the water supply infrastructure in the Gulf, and any related trade-offs or environmental impacts.
- **Incremental change:** Until the different components of the water supply system are fully developed, the brine management issues can still be tackled through a stepwise deployment of new regulations and technologies. There is a range of incremental brine mitigation options including brine minimization strategies, the use of alternative materials and chemicals, or redesign of brine discharge outlets and pipelines [5,20,21]. Furthermore, discharge monitoring systems can be enhanced to trace factors such as temperature, conductivity, TDS, dissolved oxygen, and residual chlorine at the outfall seal pit. Based on better monitoring, regulators can choose to tackle certain parameters or provide incentives to improve the technical and environmental performance of certain plants, particularly older or higher-polluting ones.
- **Auxiliary strategies based on collaboration:** Considering the small number of large plants (e.g., in Qatar), there are many opportunities for a close cooperation between the desalination industry, regulators, and the scientific community. This research on brine management shows the need for enhanced collaboration to gradually address the environmental impacts of desalination through technical solutions and collaboration. Such a collaboration could identify entry points for enhancing the performance of desalination plants through joint action or learning from other cases – including a Gulf-wide industry-academia-state cooperation on desalination. Collaboration through science diplomacy with the involvement of governments and industries can tackle increased pressures on the Gulf as a shared regional sea [69]. It can be geared towards enhancing a circular water economy in the long run and across the desalination water cycle. There are numerous available circular options relevant for desalination [5,13,70], and future research can illustrate the impacts of these strategies at the level of the desalination plant.
- **Re-assessment of water security strategies:** In the particular context of Qatar and similar Arab Gulf countries, the environmental impacts of desalination cannot be solved as a purely regulatory or technical issue in isolation from broader water security strategies. These strategies have favored an approach based on large water infrastructure coupled with large consumption footprints and a

cautionary approach towards the expansion of water reuse. In reassessing long-term water security, it is important to scrutinize the large water-use footprints, the lack of acceptance of close-to-person uses of recycled water, or the viability of more decentralized desalination approaches. Here, recent water policies in the Gulf countries have placed some emphasis on resource-use efficiency (through technologies and improvements in infrastructure; e.g., reducing water loss in infrastructure). In view of this, environmental policymakers in the Gulf should contextualize desalination as a necessary option that should evolve to become more environmentally friendly and, at the same time, complement and benefit from other components (technical and non-technical) of a sustainable water supply system.

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Mohammad Al-Saidi: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ann-Katrin Ellermann:** Writing – original draft, Investigation, Formal analysis. **Markus Frederic Fittkow:** Writing – original draft, Investigation, Formal analysis. **Tobias Romanus Perillieux:** Writing – original draft, Investigation, Formal analysis. **Imen Saadaoui:** Writing – original draft, Investigation, Formal analysis. **Radhouane Ben-Hamadou:** Writing – original draft, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wri.2024.100259.

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