Water Resources and Industry 30 (2023) 100225

Contents lists available at ScienceDirect

Water Resources and Industry

journal homepage: www.elsevier.com/locate/wri

Governing desalination, managing the brine: A review and systematization of regulatory and socio-technical issues

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ARTICLE INFO

Keywords:
Brine management
Desalination
Economic regulation
Environmental management
Water governance
Water reuse

ABSTRACT

Desalination has become an attractive option for addressing water needs or solving problems of increasing water scarcity and short-term supply interruptions. However, several negative environmental impacts are associated with the resulting brine, for which a range of treatment, recovery, and disposal technologies have been suggested in the academic literature. Despite this, the technological emphasis fails to explain the absence of sustainable practices in many countries or the roles and responsibilities of involved actors. There is also a lack of consistent conceptualizations that include regulatory and governance-related issues. In this review paper, we examined the brine management issue in desalination activities as a socio-technical issue that needs to be embedded more strongly within governance and regulatory frameworks. Case experiences and options related to command and control, economic regulation, market-based approaches and public support are discussed and linked with brine management practices. This review paper shows that baseline regulations such as standards, assessments, and thresholds are still emerging, but they need to be complemented by approaches focusing on desalination costs and environmental performance. Overall, cross-sectoral collaboration in designing local brine regulation options is important for solving the brine issue. There is a need to create a joint action arena between the desalination industry, the public sector, and actors involved in innovations related to brine management. Besides, public leadership, through providing incentives and investments, is highly valuable for sustainable brine management. This leadership should address the cost of brine treatment or the required infrastructural development.

1. Introduction

Desalination as an alternative water source or a supplement to conventional water supply sources is often associated with rising water demands, overexploitation of renewable freshwater resources, and increased water scarcity. Billions of people already live under conditions of severe scarcity [1,2], and as a result, the number of desalination plants is constantly rising. There are around 16,000 plants in 177 countries, mostly used for satisfying domestic and municipal water demands [3]. Despite the investment requirements for desalination in terms of money, valuable coastal land, and energy, desalination is seen as an indispensable water source in many naturally arid regions (e.g., the Middle East) or in countries with diminishing water availability [4,5].

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https://doi.org/10.1016/j.wri.2023.100225
Received 16 April 2023; Received in revised form 1 August 2023; Accepted 29 August 2023
Available online 30 August 2023

The rise in desalination is also related to advancements with regard to its related technologies and its economic feasibility. The cost of desalination has been decreasing in recent decades due to many factors such as membrane desalination technologies (e.g., reverse osmosis (RO)), better energy recovery technologies, or operational innovations [1]. The cost is dependent not only on technologies but also on the type of water, the plant's size and the energy source, while recent cost reductions are largely associated with the expansion and vast improvements made in RO technologies [6,7]. With desalination becoming cheaper and more efficient, environmental externalities, particularly those related to the impacts of the brine, have not yet been fully solved, and, if internalized through environmental regulations, desalination costs could rise again [7]. In addition, membrane-based desalination, such as RO, discharges denser brine concentrate since it generally has a higher recovery ratio in comparison with conventional multi-stage flash (MSF) or multi-effect distillation technologies frequently used in the Arab Gulf countries [3,8].

With increasing desalination activities and more advanced technologies, the increased volumes of the (more concentrated) brine have been a cause of environmental concern due to their negative impacts on vital ecosystems such as groundwater or marine ecosystems [9,10]. Environmental impacts of the brine discharge are associated with certain characteristics of the desalination brine, e.g. salinity, temperature, turbidity, and chemical and metal contents. For example, if these characteristics go beyond certain thresholds, they can lead to stress, declining growth and mortality of marine organisms [11–13]. As a result, increasing attention is being paid to technologies that can manage, minimize, utilize or eliminate the brine (e.g., Refs. [14–16]. The basic premise is that advances in "green" desalination technologies can mitigate some of the impacts of the brine [17], and that desalination in general should be more sustainable in using inputs (e.g., water and energy) or discharging outputs (the brine or emissions) [18–20]. However, within this and other technology-centered academic literature, less focus has been put on governance and regulatory remedies, which are largely missing in major brine-producing countries (e.g., in the Gulf) [5,21–23]. Beside this, brine management is a complex process involving multiple stakeholders and issues, thus necessitating a systematization beyond its technological options and feasibility [4,24,25].

The aim of this paper is to systematize options for brine management by embedding it in knowledge on desalination governance as a broader collaborative and socio-technical task. Specifically, it reviews the academic literature on brine management with relevance to regulatory and governance-related options. In this paper, brine management is first introduced as a central problem within a complex set of environmental problems associated with desalination. Later, a critical reflection is provided on the largely technical studies on brine management, while an argument for a better systematization of the brine problem is made. Some analytical frameworks are then provided for systematizing academic studies on brine management and desalination governance. Furthermore, technological options are synthesized using existing overview studies, while non-technical options involving governance and regulations are presented (e.g., impact assessments, monitoring plans, incentives etc.) and discussed using cases from the reviewed literature.

2. Desalination's environmental impacts: a complex socio-technical issue

Current research into the environmental impacts of desalination encompasses a wide range of economic, social, and technical considerations; e.g., comparisons to other supply options, cost–benefit of desalination, costs of impacts, or available technological choices [25]. It is therefore important to prioritize and balance economic, environmental, and social objectives when planning for

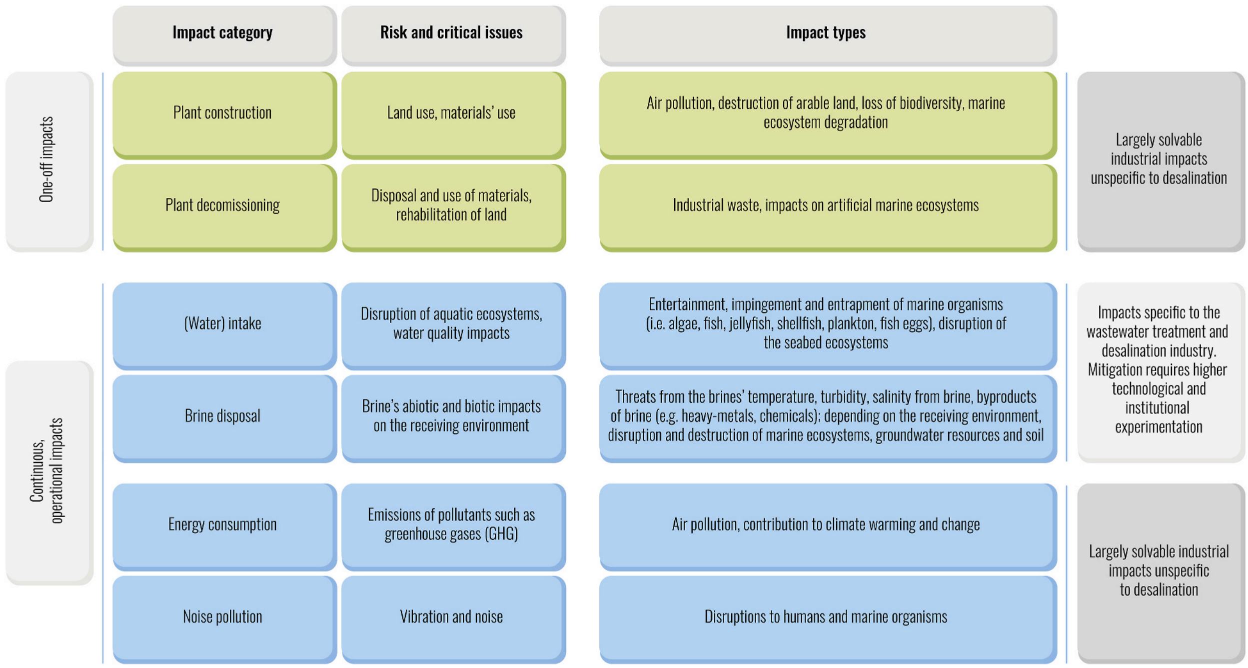

Fig. 1. Overview of environmental impacts of desalination.

desalination [4]. Environmental impacts are contrasted with water needs and alternative supplies, while countries might choose to "live with" some impacts or only mitigate some of the more serious ones, e.g., the impacts of water intake, brine disposal, or greenhouse emissions [10,13]. The causes of the environmental impacts of desalination can be seen as being related to the social and political spheres since rising demands, the lack of demand management, and the presentation of desalination as a techno-managerial panacea have been fueling desalination [26,27]. To add to this complexity of studying desalination's impacts, they are often site-specific depending on the design of the desalination plants and the receiving environments of the impacts. Therefore, evaluating such impacts requires local-level monitoring tailored to the impact and the type of ecosystem [28,29].

Brine is seen as one of the multiple environmental problems of desalination, which are summarized in Fig. 1. These impacts are also interrelated as, for example, plant construction choices can later affect impacts from water intake and brine disposal. As will be discussed later in this paper, brine management is a part of the complex operational impacts of desalination activities, which require a higher level of technological and institutional problem-solving capacity through experimentation with different techno-regulatory fixes. Detailed descriptions of the characteristics and impacts of the brine discharge can be found in review studies, particularly focusing the impacts on the marine environments [11–13]. The brine's impacts depend on several site-specific factors related the brine and the receiving environment. Here, the key brine characteristics are those related to the salinity, turbidity, temperature and chemical as well as metal contents [13]. Salinity is a key concern since it can exceed the marine organisms' tolerance, and any extreme, abrupt and persistent change can lead to physiological stress, declining growth and mortality of organisms [11,29]. Besides, species can die due to thermal shocks and decreased dissolved oxygen due to water heating [10]. The impacts of chemicals and heavy metals is twofold. They can increase water turbidity, and thus the biological activity and photosynthesis, and they affect the metabolism and growth of organisms [10]. Overall, the exact impacts on the receiving environment can vary depending on the characteristics of the brine, the specific marine environment and the deployed brine mitigation strategies, see the detailed descriptions in Refs. [11–13,29].

Impacts associated with plant construction are important within the desalination lifecycle [30], but they might be unavoidable, or can be compensated for. Desalination plants can be decommissioned due to disturbances, or on the expiry of the lifetime of a plant. It can cause impacts in terms of land rehabilitation due to the removal of unintended artificial reefs around coastal facilities [31], although such plants are often modernized, or new plants built on the same sites [32]. With regard to impacts such as air pollution and emissions, there are many mitigation options in place such as using renewable energies in order to reduce greenhouse emissions or energy recovery for increasingly energy efficiency and thus reducing emissions [18,20,33]. Besides, the magnitude of impacts from noise and vibration on marine ecosystems have not been robustly confirmed in the academic literature [17].

3. Dealing with the brine: the need for a non-technical systematization

The academic literature on the desalination brine management issue has been growing rapidly. For example, a Scopus search of publications with the words "brine" and "desalination" in the abstract, keywords or title identified more than 3,000 publications (November 2021), 2,000 of which were from 2011 to 2021, with an increasing trend (e.g., around 160 studies in 2015 cf. 260 in 2021). These studies also include several recent studies (included in the analysis of this paper) reviewing state-of-the-art technological remedies for the brine; e.g. Refs. [8,14,17,18,34–38], or environmental monitoring and impacts [2,13,19,28,29]. This is in addition to several reviews on case experiences; e.g., desalination in Spain [39] or the Arabian Gulf [16] as well as on certain technological or methodological issues; e.g., life-cycle assessment [30] or recovery technologies [14,15,18,40].

This section highlights three problems with the largely technical body of literature on desalination brine management. Firstly, the technological emphasis of the literature on brine management does not explain the reality of unregulated use and rising impacts. While many studies list an array of possible technologies for solving or mitigating the brine problem, brine disposal is still a major problem globally and is often not tackled, and its disposal into the sea not effectively regulated in major regions such as in the Arabian/Persian Gulf region [3,5,23]. The notion of the brine problem being "largely technologically solvable" can be criticized for reinforcing some problematic aspects of the rise of desalination, such as cementing a neoliberal and supply-sided model of water control [41], conveying a sense of water abundance at an acceptable cost [42], or depoliticizing water desalination as unproblematic or uncontested [27]. More practically, these technology-focused studies lack consideration of feasibility from economic and governance perspectives. For example, many of the materials' recovery technologies presented in the academic literature are largely not economically feasible or commercial [17], while energy recovery remains expensive and unstable [18]. As another example, zero-liquid discharge (ZLD) still has a large energy and material footprint, and would require a greater deal of regulatory and commercial experimentation [16].

Secondly, the current studies providing overviews of brine management technologies lack consistent conceptualizations of the different options. For the most part, they consist of descriptive listings of technologies, which are rearranged depending on the narrative or the internal organization of the study. An example of this is the ZLD idea, which is sometimes presented as a concrete technology; e.g., for recovery [8] or indirect brine use [43], as the final aim of all brine mitigation interventions [35], or as a separate "engineering approach" or "technique" with sub-systems (e.g., thermal-based and membrane-based ZLD systems) [33]. Often, the understanding of the nature of the technologies changes with the perspective; e.g., by focusing on water–energy interlinks and recovery [18,20,40].

Thirdly, social, regulatory and governance issues are rarely integrated in the descriptions of the potential of the (combinations of) brine technologies. Some studies might mention desalination economics in general, or qualitatively rank the cost of brine discharge methods [43]. However, the interlinkages between the emerging brine technologies and desalination governance are missing; i.e., which governance-related changes and supports are required to facilitate the dissemination and adoption of these technologies. At the same time, the majority of desalination governance studies are not specific to the brine problem but frequently highlight more aggregated issues such as the conceptualization of desalination [5,21,42], and/or consequences of the rise of desalination for the control and power relationships in the water supply [25,41,44].

4. Methodology and analysis framework

4.1. Literature selection and analysis

To link the academic literature on brine management to that on desalination governance, two separate literature selection rounds were carried out. First, using the peer-review databank "Scopus," a search was conducted in October 2021 for papers using the word "brine" together with any of the words "management", "policy" or "governance" in the keywords, abstracts, or titles. The resulting dataset of 409 publications was analyzed to pick out relevant papers that are not dated (oldest selected paper from 2005), not too specific (e.g., not on single technological applications/projects or on a too-specific brine problem) or immaterial (e.g., not directly connected to the brine problem). The final set of relevant and accessible papers included in the review totaled 46 publications. Another Scopus-based search was then conducted for publications with the words "governance" and "desalination" in the abstract, keywords, or title. The resulting dataset of 79 publications (2001 to October 2021), was sorted by avoiding duplication with the first search, and selecting only publications that had desalination governance as a main or core topic (e.g., not relating to governance as a side-issue or a buzzword). The resulting dataset included 13 studies, which were merged with the first dataset (giving a final dataset of 92 publications) for the analysis. To facilitate this analysis, MAXQDA was used as a qualitative data analysis tool, which helped examine and code the contents of the publications into technological and non-technical brine management options (see Section 4.). Alongside this core literature review, other publications were included for their use in developing the conceptual framework or discussing the implications of the reviewed options.

4.2. Analysis frames: water supply governance vs. desalination management

The brine management issue is a complex endeavor that is often not clearly assigned to certain actors and processes. The earlier-mentioned technology-focused studies on brine management do not include prescriptions on roles and responsibilities. They would rather assume that brine technologies are implemented at the desalination plant "at some point" if they become commercially and technologically mature enough. The pathway from "technologically addressing the brine" to "sustainably managing the brine in practice" remains vague. Brine management strategies are often implicitly considered to be the desalination industry's job or a result of the industry's development or innovation [3,19,40]. However, desalination plants might be unable or unwilling to manage the brine, since they need to differentiate their managerial perspective on their day-to-day desalination operation from the broader perspective of water supply governance (Table 1). Desalination is one (or sometimes the only) option in water supply governance for certain water-use purposes, which should be secure or reliable and provided with an optimal use of resources (e.g., through competition or the correct economic regulation). Desalination managers are arguably more concerned with operational continuity, optimization of processes, and addressing any risks. The notion of supply risks as a guiding security notion in desalination plants is becoming increasingly important for desalination plants [45]. It is also important to think of brine management as a governance issue related to the environmental challenge (i.e., the overall regulation of industrial degradation) and social equity (providing affordable access). In line with this, several studies have framed brine management as a governance issue (and not merely a management task) [21,22]. For desalination plants, brine management is often conceived in terms of compliance with environmental regulations in countries with regulatory frameworks; e.g., Spain [46]. Besides, recovering costs and desalinating water at an affordable cost are the main concerns of industrial desalination projects around the world [6,7].

Overall, it is important to conceptually separate the two perspectives described in Table 1. As will be explained in this paper, to effectively address the brine issue, it is important that there are both technological and institutional remedies as well as cooperation that bridges the brine management–governance gap. Fig. 2 explains this argument further by highlighting the categories of options for addressing the brine issues from a governance and regulation perspective as well as a brine management perspective. These options will be investigated in this review by first synthesizing technological options (Section 5.1) and later introducing brine-related

Table 1
Example frames of sectoral and plant-level perspectives on desalination.

Orientation frames	Water supply sectoral perspective (governance)	Desalination plant perspective (management)
Security	*Long-term supply reliability:* advancing desalination as a reliable and long-term water supply option through a well-performing and secure desalination sector	*Operational continuity:* securing operations through minimizing risks of interrupting activities due any human or technical failures
Efficiency	*Economic efficiency*: ensuring optimal use of economic resources through creating conditions for competition (e.g., private sector participation) and eliminating market distortions	*Technical efficiency:* improving efficiency in production through monitoring and optimizing processes, training, and knowledge
Sustainability	*Regulation of desalination's environmental footprint:* Setting up institutional and policy frameworks for controlling desalination activities	*Compliance with environmental regulation:* monitoring environmental impacts of operations and adhering to existing thresholds and legal requirements
Equity	*Affordability:* ensuring affordable and widespread access to clean desalinated water; e.g., through subsidies for low-income households if necessary, and monitoring the impacts of water prices	*Social responsibility and cost-recovery*: aiming at cost coverage while reinvesting part of access revenues in demonstrating (corporate) social responsibility

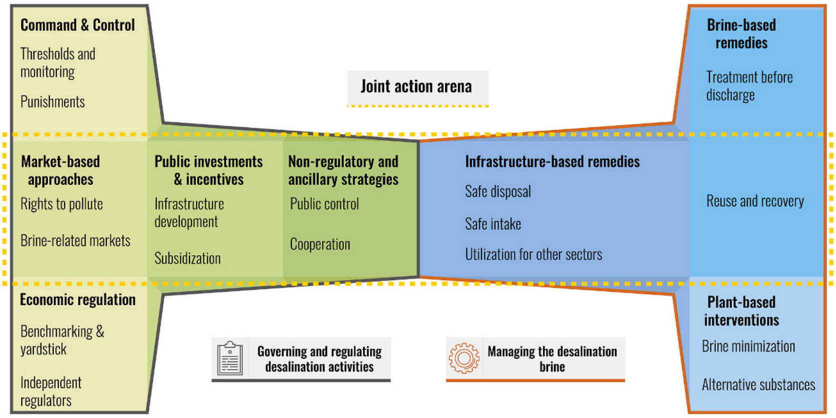

Fig. 2. Governing and regulating desalination vs. managing the brine.

governance and regulatory options (5.2). The review of technical and non-technical options will create a joint action arena where sustainable management strategies are facilitated by collaboration, (public) support, and good desalination governance.

5. Results

5.1. Technological mitigation options for desalination brine: a critical synthesis

The majority of the reviewed studies on brine management put forward several technological options that can be organized depending on the use purpose (e.g., recovery, minimization, reuse) or the step in the desalination process (e.g., intake, handling, or outtake). In order to synthesize the most prominent options, Table 2 organizes them based on the primary focus of technologies, while some critical factors are presented. In order to later link brine technologies to non-technical aspects of regulation, governance, and public support, we differentiate between whether the options are focused on i) infrastructural development, ii) brine handling/processing, or iii) the desalination plant's operations. Firstly, infrastructure-based remedies are arguably the most ambitious ones in terms of requirements for accompanying strategies such as site selection, transport, investments in other sectors, and research. For example, making the brine suitable for use in other sectors requires careful testing, preparation, and infrastructure [52,53]. Similarly, achieving ZLD is an ambitious aim, necessitating collaboration with other industries; e.g., for energy and land provision as well as for receiving recovered materials [16]. Other options for disposal in safe places (deep wells, sewerage, inactive zones, etc.) are difficult for high-capacity desalination if there is no prior regulation and infrastructural investment. Secondly, brine-based remedies are common and more accessible technological solutions focusing on reusing, recovering and treating (certain components of) the brine. Although these options can be implemented during the processing of the brine, and thus not necessarily requiring significant investment in other sectors, research and collaboration with other sectors (e.g., as customers for recovered materials) can make some of some costly technologies more feasible [14,15]. Thirdly, plant-based interventions are low-hanging fruit in terms of improvements in the plant operation towards optimizing the recovery ratio, or the use of chemicals/substances. Such interventions should be locally determined through the process and innovation management of operations at the desalination plant.

5.2. Regulatory and governance-based propositions: extending the options

5.2.1. Command and control

Command-and-control regulations rely on instruments enforced "at arm's length;" i.e., through setting standards/rules and controlling compliance with them. In governing desalination activities and managing the brine, this type of regulation is the most typical one. Table 3 provides an overview of commonly used instruments as well as their scope and dissemination. Two remarks can be made here about this category of options. Firstly, command-and-control regulations build a sort of foundation for governing the desalination sector. They start with the construction of the desalination plant and cover the lifetime of the desalination activities. Although there will often be a need for updating and adapting such regulations (adding new indicators, or more flexible and site-specific parameters) [39,55], having a bedrock of standards and rules is key for sustainable desalination.

Secondly, a high degree of flexibility and diversity can be observed with regard to the dissemination and design choices of command-and-control instruments. These instruments cover desalination's environmental impacts at large, although the brine issue, particularly the control of salinity thresholds, is a predominant one [46]. They can be combined and further specified depending on the regulatory culture in a country or region. A more comprehensive approach would include strict EIA requirements specified for desalination plants, with regularly enforced and threshold-based EMPs as well as additional protocols for emergencies. This is, for example, the regulatory ambition in the well-documented case of Spain, although difficulties with regard to monitoring, choice of indicators, and specificity of monitoring plans have been reported [39,46,47]. Quality thresholds for brine discharge serve as the "lowest common denominator" for brine discharge since they even exist in cases with low regulatory levels and enforcement

Table 2
Overview of major technological solutions for brine management.

Category of solutions	Sub-category	Major types of solutions	Description of (technological) applications	Critical aspects and literature
Infrastructure-based remedies	Utilization for other sectors	Hydrotherapy	Use for therapeutic and healing purposes (brine pools)	Does not eliminate the disposal problem; option still to be introduced [43]
		Land application	Use for saline irrigation; use for the regeneration of coastal and inland wetlands	Soil salinization in irrigation as a challenge [13]; wetland regeneration does not eliminate the brine [43].
	Safe intake		Reducing feedwater velocity; adding physical barriers and bypass systems for preventing impingement; choosing hydrologically active (but less biologically productive and endangered) areas for intake; preventing erosion of pipelines	Each safe intake technology/intervention should be assessed and tested locally [17].
	Safe disposal	Zero-liquid discharge	Combination of different technologies characterized as minimum-liquid discharge (MLD) zero-liquid discharge (ZLD or ZLQ) or zero-liquid desalination aiming to eliminate the bine by either increasing feed recovery rate (e.g., near 100%) and/or converting liquid waste to solid products	Variation of experimental plants and methods depending on the brine and local conditions but largely considered as a future pathway for desalination [8,9,17,34]; complex, and energy- as well as emissions-intensive process with more regulatory requirements needed for technologies and uses [16]; eliminating liquid brine is rather a research agenda or a final aim of desalination rather than a technology or a concrete approach in itself [1,25].
		Surface or deep-well injection	Discharge into surface water, sewerage networks, rock formations or deep aquifers	Pollution and destruction of (vulnerable) ecosystems [13]; deep-well injection has higher costs than other methods and difficulties preventing leakage, leaching and corrosion [16,34,35]; various drawbacks, e.g., from inhibiting bacterial growth, increasing salinity, or overwhelming the capacities of wastewater treatment plants [13,34,35]
		Discharge in specified cites (discharge zones)	Discharge in highly regulated and specified discharge zones (e.g., deeper areas with high-turbulence hydrodynamics)	Strong regulations as a general principle for any discharge strategy [13,47]
Brine-based remedies	Reuse and recovery	Carbon sequestration	Use of reject brine for CO_2 capture, storage and utilization	Several feasible technologies using adsorbents and CO_2 conversion technologies [17]; disposal of CO_2 through injection into groundwater aquifers can create brine [40].
		Recovery of minerals, salt and precious materials	Various (combinations of) technologies for recovering minerals, salt, metals and other materials from the brine	Depending on salt markets and consumption, salt recovery can be profitable [35]; technologies for metal recovery are still immature for industrial-scale applications [8]; no single stand-alone technology is best for mineral recovery (rather a combination of technologies) [18]; despite many experiments to extract precious materials (e.g., magnesium, gold, uranium, bromine, potassium, cesium rubidium and lithium) from brine, processes largely not economic/commercial at the moment [17]; more research needed on economic feasibility, business cases and environmental impacts on each recovery technology [14,15]
		Energy recovery	Recovering energy from brine; i.e., chemical energy resulting from the salinity gradient (Salinity Gradient Power or SGP)	Many of the SGP technologies remain expensive, poorly performing, and vulnerable to fouling of used membranes [18]; energy recovery as a promising but still emerging option [1,18,48]
	Treatment before discharge	Adsorption	Use of adsorbents as a way to remove salt, organic compounds, heavy metals, or other pollutants	Need for adsorbents with high adsorption to ensure large-scale feasibility [34]; (bio) adsorption as a novel treatment method requiring a high level of selectivity and experimentation with used materials [40,49]
		Evaporation ponds	Evaporation of brine in pond and gathering residual salt	Common and accessible technology, but groundwater pollution and soil salinization should be avoided [13]; other considerations include pond size, maintenance, land use and continuous operation, while technology is rather expensive (e.g., 10 USD per cubic meter) and operational for low capacity only [34]

(*continued on next page*)

Table 2 (*continued*)

Category of solutions	Sub-category	Major types of solutions	Description of (technological) applications	Critical aspects and literature
		Disinfection	Considered as a pre-treatment step using various disinfection techniques such as chlorination	Chlorinated solvents negatively impact aquatic ecosystems [34].
		(Pre-)Dilution	Mixing brine with seawater or other water types and/or increasing the disposal area for spreading the brine in the sea through using multiple mixing zones or processes (e.g. attaching diffusers to existing or new outfalls) and discharge points	A common and cost-effective approach but requires careful planning and regulations [43,48]; dilution might reduce pollution but does not reduce salinization or heat discharge [16]; pre-dilution (blending with other water prior to discharge) as a traditional strategy to minimize brine impacts with the use of diffusers in submarine discharge as the most widely use solution due to their high dilution capacity [50], pre-dilution solutions should be checked against pumping costs [51]
Plant-based interventions	Incremental brine minimization		Approaches to increase recovery rate; e.g., incremental update/enhancement of desalination technologies	No clear stand-alone technology to incrementally increase recovery rate, while most brine minimization strategies require changes/ investments in new systems [34].
	Incremental decrease of other substances		Efforts to incrementally decrease use of chemicals and other pollutants	Requires alternative materials and comparison of the impacts on the required quality of the final desalinated water.

mechanisms such as the Gulf [16]. The selection of (the combination of) regulations and how they are institutionalized varies by jurisdiction. For example, while EMPs and EIA are required in many countries such as the USA, Australia, Spain, Chile, Israel and Saudi Arabia, the latter three countries have low requirements associated with EIA and EMPs [56]. Other countries, such as Tunisia, the United Arab Emirates (UAE), Oman or Algeria seem not to require EMPs in most cases [56]. Furthermore, in Israel, special monitoring requirements are required for the 30-km long brine disposal pipeline developed as part of a rehabilitation project for a coastal aquifer by removing underground saline and transporting the brine to the sea [57].

5.2.2. Economic regulation as a comprehensive approach

Economic regulation is a comprehensive approach that is often used in the water supply sector and aims at monitoring and regulating the performance of the service providers [58]. There are many possible economic regulatory measures with different degrees of enforcement; e.g., from collecting performance data to imposing monetary incentives or punishments. However, the bulk of economic regulations center on price-setting through surveillance and influencing the cost function of utilities [59,60]. In contrast to command-and-control, economic regulation allows for consideration of technologies, since regulators need to closely examine the production function of water providers. Current practices of water sector regulation, e.g., desalination in Australia, are increasingly being considered as one bulk supply issue that could increase the cost to water providers [61]. With a growing reliance on desalination, sustainable desalination, brine management, and the effects on water costs can be emphasized within comprehensive frameworks for water-sector regulation and/or necessitate novel economic instruments. Some of the typical economic regulation instruments are mentioned in the following:

5.2.2.1. Rankings, benchmarking and yardstick competition. Gathering and publishing performance data on water providers is a common factor in economic regulation approaches [59,62]. Performance can be compared between the providers or by using an external or internal benchmark (in some cases a hypothetical "efficient" provider) in a way that encourages providers to emulate the benchmark. Benchmarking and ranking of providers can deliver more transparency or competition through "naming and shaming" providers (sometimes called "sunshine regulation"), or it can serve as an entry point for yardstick competition, which often involves providing incentives or setting the prices (i.e., a carrot-and-stick regulation) [63,64]. For desalination plants, there is little evidence of comprehensive benchmarking, although it is feasible to include such instruments independently (including parameters on brine management) or as part of the economic regulations of water utilities. For example, Al-Sharrah et al. [65] provided an environmental ranking methodology for desalination plants in the Gulf. They reviewed other environmental assessments, including brine discharge. Such ideas present viable directions for larger performance-based regulation of desalination plants.

5.2.2.2. Independent economic regulators. Independent regulators for water service providers based on the idea of economic regulation exist in Latin America, Australia, Europe and the Arab region [59,61,66]. For desalination, some issues related to the cost of bulk water supply are being considered by water regulators while environmental pollution, e.g., from the brine, is often monitored by independent environmental authorities. However, both water and environmental regulators are increasingly becoming involved in desalination-related issues. For example, the water supply regulator in the UK, Ofwat, is involved in scrutinizing the costs and merits of options to reduce abstractions during the drought in Hampshire. In its recommendation in 2021, the regulator initially endorsed the consideration of solutions such as water recycling, water transfer, a reservoir in Bristol, and a desalination plant that would be the largest in the UK (up to 75 million liters per day) [67]. In Kuwait, the Kuwait Environment Public Authority is increasingly involved in

Table 3
Commonly used command-and-control instruments for brine regulations.

Regulation instruments	Description	Scope and examples of dissemination
Environmental impact assessments (EIAs)	Common requirement for new desalination plants; the process of developing EIAs mainstreamed and defined by regulators	Different types of EIAs (e.g., environmental impact studies, evaluation systems or declarations) used in Chile depending on the specific project/site and expected impacts [28]; used in the Gulf region although not consistently applied, with a lack of robust before-after-control impact (BACI) monitoring [16]; EIAs used in many countries with varying requirements and problems; e.g., unenforced regulations in Saudi Arabia [22], disparity in salinity thresholds and irrelevant parameters in Spain [18,46,54]
Environmental monitoring plans (EMPs)	Usually developed together with EIAs to identify negative environmental impacts, outline monitoring procedures and action for mitigating impact [28]	Commonly used in Chile with an increasing trend in control requirements in EMPs [28]; EMPs used in Spain, with long-term EMPs suggested for more rigorous environmental assessment [55], and more flexible EMPs using new indicators (e.g., bioindicators) [39]; EMPs in Spain include four areas of control levels: i) flow of seawater and brine, ii) surroundings of discharge zone, iii) receiving seawater, iv) protected marine ecosystems [47]
Setting of water quality thresholds/ standards	A less extensive approach than EMPs through setting standards or thresholds for receiving environments or brine characteristics; e.g., temperature, salt, or chemicals; thresholds can also be set within EMPs.	Standard-setting can include disclosure mandates for volumes of treated brine, used additives and properties of discharge [16]; thresholds for salinity of brine discharge applied across the world (e.g., USA, Canada, Australia, Saudi Arabia, Oman, Israel, or UAE) [16]; salinity thresholds can be applied for certain species affected by the brine [16]; in Saudi Arabia, desalination plants lack monitoring of compliance with discharge standards [22]; in Kuwait, the Kuwait Environment Public Authority assumes water quality monitoring to verify compliance with thresholds [29]; in Europe, the Water Framework Directive (WFD) addresses salinity levels of disposed brine, but strict regulations are limited to groundwater injection [18]
Setting mixing/brine zones	Assigning or regulating certain zones where the brine can mix with another water source; e.g., certain areas to discharge brine into seawater with minimal impacts	A common approach for regulating the brine discharge in North America and Israel, with mixing zone characteristics depending on the characteristics of the brine and receiving environment [18]; in the USA, different models used by regulators to determine mixing zones and expected impacts [48]
Emergency regulation	Additional measure stipulating action if an environmental quality threshold is exceeded or if other irregularities occur	In Spain, an additional action protocol is enforced in the case of irregularities including responsibilities to find the cause and/or modify operations (e.g., prior dilution, reducing flow, or decreasing recovery rate) [47]
Sector-wide regulation: protection areas; strategic impact assessment (SEA) and marine spatial planning (MSP)	Development of sector-wide regulations; e.g., for marine ecosystems within which desalination plants operate	SEA can be developed for a sector (e.g., marine ecosystems or domestic water supply) or a specific activity (e.g., desalination) to address cumulative environmental impacts, while MPS as a regional planning approach can define acceptable loading limits for certain areas [16];

monitoring and regulating, through command-and-control measures, the increase of salinity in the Gulf due to brine discharge [29]. Considering the rise in desalination, ca. 16,000 plants worldwide and hundreds of plants in countries such as Chile and Spain [3,28,53], it is worth considering the introduction of independent regulators or increased tasking of desalination issues to current water sector regulators. With desalination becoming an important element of contingency planning, there is an argument for reassessing economic regulation in order to ensure cost recovery through water tariffs [68]. At the same time, economic regulations should not be confused with more legal bureaucracy, as it essentially entails working closely with the water providers to improve their performance, efficiency, and sustainability [66]. If regulators choose to tackle the brine issue of desalinated water, there is a wide range of options available, which include direct regulation through price-setting models, indirect regulation through price/performance monitoring, and regulatory negotiation and arbitration [61].

5.2.3. Market-based approaches

Another possible regulatory approach that can be taken without, within, or in addition to comprehensive economic regulation is the reliance on market-based instruments. Market-based approaches are commonplace for solving pollution problems. They are assumed to be more efficient than command-and-control instruments in cases with many and heterogeneous providers, since the regulator needs only to identify the aggregate costs of abatement (and not the individual costs for each provider) [69]. Some common and new instruments based on markets are introduced in the following section.

5.2.3.1. Property rights and market-based incentives. The range of instruments under this category ranges from direct ones, such as effluent charges and tradable permits based on the idea of buying the right to pollute, to indirect instruments such as environmental taxes or subsidies for substitutes and abatement [69]. These instruments are widely used in environmental management across the world, and they bring with them various variations, pros and cons, and controversies [70]. In the water sector, tradable permits have been applied in many countries (e.g., the USA, Australia, China, Chile, Mexico, South Asia) to cap certain water pollution parameters or as tradable water abstraction rights [71]. However, tradable permits might face problems if there is no competition in the market or due to poorly defined rights and high transaction costs [71]. So far, there is no evidence of the dissemination of these instruments in the desalination sector. While some cases (e.g., Spain, Oman and South Africa) have reported the use of discharge permits [18,21], there is no evidence that these permits are tradable. On environmental taxes and incentives, Kesieme et al. [72] reported that carbon taxes will increase the cost of desalination. Munguía-López et al. [73] emphasized the beneficial impacts from carbon and water taxes (for penalizing abstractions) on aquifers with desalination plants in Mexico, as well as water tax credits as monetary compensation for sustainable practices.

5.2.3.2. Brine-related markets. Conceptually, market-based incentives can be applied to desalination and its brine issues, particularly if competition increases in this sector. With the increasing role of private companies as well as private–public partnerships in desalination in cases such as the USA, the Middle East, Africa and Spain [53,74,75], one can expect market-based instruments to be more attractive in the future. Instruments such as taxes, tax credits, and tradable pollution permits can increase the cost of desalination and water supply, but, at the same time, they make brine management more feasible. In this way, high-recovery options such as ZLD can become more attractive since the high cost of treatment (compared to the water price) is the major market barrier to these options [76]. Historically, regulatory requirements have been the primary drivers for high-recovery processing of the brine, but the high cost and the novelty of recovery technologies have impeded their wide acceptance and adoption [76]. In theory, the cost of developing and applying these technologies can be subsidized. The recovery of precious materials can generate significant revenues (e.g., 18 billion USD per year in Saudi Arabia), while the feasibility of recovery is a function of the technology cost (including any subsidization), the price of precious materials, and the desalination price (including the pollution costs and subsidies) [15].

5.2.4. Public investments and support

With the lack of competition in the desalination industry, the public's role as service provider and asset owner is strong in regions such as the Middle East [5]. In the Gulf, for example, desalination is highly centralized in a small number of desalination plants, which are in the hands of public operators [45]. As a result, the public sector is actively involved in developing and upgrading desalination infrastructure. Public involvement in desalination is generally associated with greater viability of desalination projects, as governments can provide commitments, assurances, and subsidies for new technologies such as renewables or new disposal processes [56]. New plants based on public–private partnerships (PPPs) receive significant public support such as guaranteed water purchase agreements or contributions to fixed costs [74]. In the Gulf region, many independent water and energy producers are receiving hidden subsidies in terms of fuel, guarantees and risk-sharing [77,78]. The involvement of the private sector can allow for technical innovations and experience in managing issues such as the brine, although it can be associated with higher costs and negative public perception [74]. As illustrated in the case of Israel's public Mekorot company, public support can ensure investments in expensive mitigation options such as brine transport infrastructure [57]. Public investments can also be directed toward the development of cleaner desalination technologies through cost-sharing or the provision of research and development funds [17].

5.2.5. Non-regulatory and ancillary strategies

In addition to monetary and infrastructure support to public, private or mixed operators, one non-regulatory strategy is to maintain public control over desalination. In many cases, such as in Spain, desalination is governed as a public water resource, and concessions are required for private operators [53]. This public control strategy might be important in the face of the risks of the neoliberal model of "water commodification" or through PPPs in controversial cases such as in California [79]. In many PPP cases, desalination concessions are made through build-operate-transfer (BOT) arrangements, which require a clear enabling regulatory framework to ensure accountability and public control as well as to define risk-sharing [74].

Some other ancillary strategies mentioned in the academic literature on desalination and brine management are related to cooperation and collaboration. One aspect of cooperation is the private–public cooperation with regard to the earlier-mentioned involvement in desalination supply, but also in finding arrangements for mitigating investment risks in desalination and innovative brine technologies [24]. Collaboration in innovation, including R&D and piloting of brine technologies, is also key for sustainable desalination [24]. Sola et al. [39] stress the importance of providing scientific advice as a collaboration between engineers and the environment during the development of desalination projects. Hosseini et al. [29] emphasize in the case of the Gulf the importance of regional cooperation between riparian states sharing the problem of increased environmental pollution in this water body. Similarly, Al-Saidi and Saliba [45] emphasize this point with regard to emerging risks facing large-scale coastal infrastructure such as desalination plants.

6. Discussion

6.1. From brine technologies to brine regulation and governance: overarching insights

Current knowledge on brine management is heavily skewed towards technologies with few insights into action towards institutionalizing these technologies through regulations, incentives, and governance mechanisms. This paper addresses this gap by systematizing the brine debate and reviewing the knowledge on brine management technologies and their links to non-technical mitigation measures. In doing so, we argue that, in order to approach feasibility and scope, brine management options can be viewed with regard to their problem-solving approach; i.e., remedies based on infrastructural development, brine treatment technologies, or optimizations in the plant's operation. They should also be examined based on the required facilitating factors in terms of issues such as regulations, costs, and collaborations. In this section, we summarize some overarching insights from our high-level review of brine management and regulation. However, there is a need for more local studies on how certain regulatory and governance instruments have facilitated the adoption or feasibility of a specific brine management option. This is in line with other studies that stress the site-specificity of brine interventions, particularly those related to disposal options and reuse in other sectors [38,57]. The following is a discussion of some aggregated insights from this paper:

- *Unequal regulatory environments*: Regulatory practices are uneven with many countries, particularly in the desalination big-player countries of the Gulf, reporting a lack of sufficient and/or enforced regulatory frameworks [21–23]. The cases described in this review show that command-and-control measures are the most frequently deployed ones, with Western desalination countries, e.g., Spain, the USA and Australia, reporting the longest-established regulatory environments. In fact, surveys on regulatory requirements in the global South are inconsistent, with many countries indicating either lack of or inconsistent use of basic instruments such as EIAs and EMPs [56].
- *Diversity and building blocks of brine regulation:* Alongside command-and-control measures, there is a highly diverse range of other regulatory instruments. Regulation means choosing and combining certain instruments depending on local conditions. Command-and-control regulation represents baseline instruments such as authorizations, environmental assessments, and monitoring procedures. Economic regulation allows for greater engagement with the technologies and cost function of service providers, and offers promising ideas for future applications with the increasing pace of desalination activities. Instruments based on markets might require more competition [70,71]. The regulatory portfolio in each case should select instruments based on local conditions such as the heterogeneity of the supplier or the financing and organization the desalination sector.
- *Public involvement and infrastructure-based remedies:* Many problems have been highlighted related to infrastructure-based remedies; e.g., cost, acceptance, site selections and environmental requirements. To accommodate some of these problems, public involvement is important in terms of setting the right economic incentives (i.e., risk-sharing and lowering the cost of brine management) and investments in brine-relevant sectors (e.g., R&D, piloting, transport infrastructure). Progressive brine technologies such as ZLD and reuse in other sectors imply beneficial externalities that can be harnessed through expenditure on innovation and infrastructure, with some promising steps in this direction witnessed, for example in the EU [24].

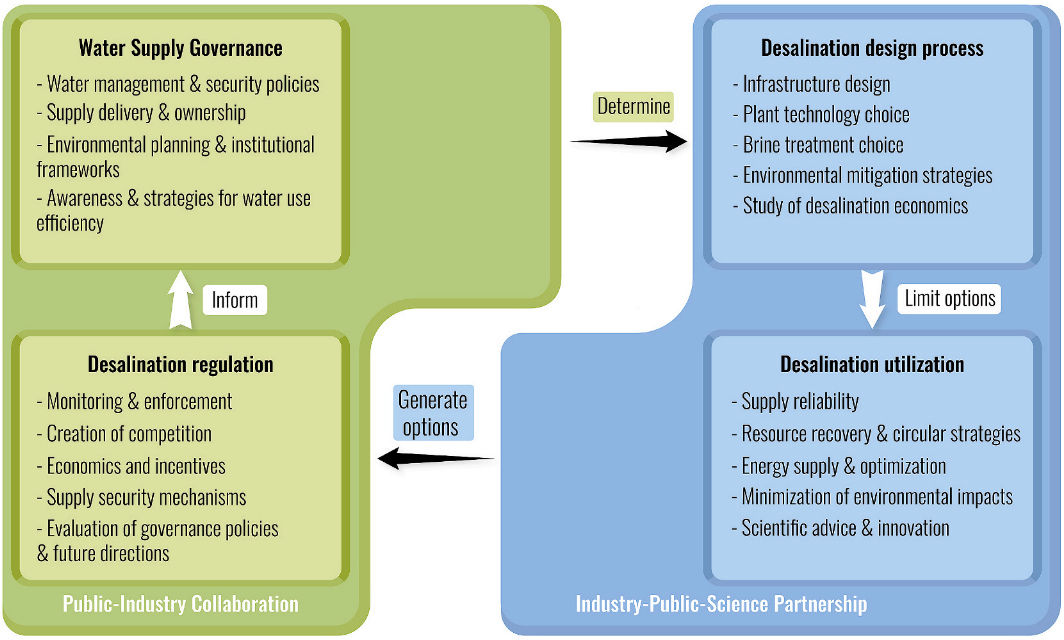

Fig. 3. Comprehensive brine mitigation as a multi-facetted, socio-technical issue.

- *Maturity and support for brine-based technologies*: Many brine-based technologies for recovery, carbon sequestration and required treatments are at different levels of commercial maturity. While some methods such as (pre-)dilution and the use of diffusers in subsurface brine discharge are already common and feasible (see Table 2), the lack of regulations (particularly through command-and-control standards) is seen as a major obstacle. For other technologies emphasizing recovery and reuse, market-based instruments (e.g., pollution rights or tax incentives) are key to solving the pricing issue.
- *Low-hanging fruit*: Supportive strategies for regulating the brine issue include cross-sectoral collaboration, stakeholder (and regional) cooperation and public leadership. These strategies represent low-hanging fruit in the move towards some (incremental) change in sustainable desalination. With governments involved in controlling and managing many desalination operations, more investments can be facilitated via simple remedies such as plant-based optimization, safe-intake techniques, or brine mixing and dilution.

6.2. Brine mitigation as a multi-facetted, socio-technical problem

This paper has emphasized the need for embedding brine management as a socio-technical issue with a larger understanding water supply governance. This is in line with research showing problems with perceiving the brine as a purely technological issue, or as a primarily management issue. For example, Swyngedouw and Williams [27] have criticized the depoliticization of water governance through a focus on a desalination fix as a techno-managerial issue. Other authors have highlighted how the propagation of actors involved in desalination is changing social relations, water control, stakeholder relations, and notions regarding water governance [41,42,75]. Desalinated water might be an export commodity in the future, which could lead to a broadening of governing institutions (including transboundary ones) and a wider diversity of stakeholders [80]. Water transfers and the application of desalination to new water types require a clear socio-legal terrain important for water governance [44]. At the same time, solving desalination pitfalls such as the brine issue is a multi-actor task requiring collaboration among stakeholders [24].

Fig. 3 summarizes the notion of embedding the mitigation of desalination's impact, such as with brine management, within a larger cycle of desalination-based collaboration and partnership. Water supply governance sets up the rules of the game for desalination activities in terms of policies, ownership, and objectives. Furthermore, several studies have emphasized the need to embed desalination within broader environmental planning objectives for certain water bodies, river basins, or regions in terms of supply security, pressures and responses, including measures of infrastructure development and restoration [34,80]. In addition, awareness, consumer perception, demand management and broader water efficiency plans are important for accepting desalination as a sustainable or welcome option [16,81]. The design process of desalination includes many choices regarding technologies, costs and environmental mitigation strategies that limit the options available for addressing many of the environmental impacts such as the brine management options described in this paper. It might be difficult to alter these decisions once a desalination plant is designed and built (path dependence). In designing and utilizing desalination plants, partnership among the desalination industry, science, and the public sector (in offering support for sustainable design and environmental mitigation) is extremely important. This partnership determines the options available for desalination regulation through the instruments mentioned in this paper. The outcomes of this regulation inform higher-level decision-making on governance choices of water supply on a large scale.

7. Conclusions

Brine management issues are some of the multiple environmental problems of desalination that interrelate and are often defined by the plant design issues and water intake. The brine issue has been tackled in numerous reviews and case experiences focusing on feasible and future technologies. However, there is a need for a systematization that considers the brine problem as a socio-technical issue demanding regulatory and governance frameworks. The technological focus on the brine management issue does not explain why brine's environmental impacts are largely unregulated and unsolved.

There is a need for consistent conceptualizations of the brine management issue that integrates social, regulatory and governance issues. Current brine management technologies vary considerably with regard to their commercial development and the required level of intervention. To link them to their regulatory issues, this paper has conceptualized technological options as related to infrastructure development, brine handling, or plant operations. Some of the overarching conclusions of the paper can be summarized in the following. First, there is a need to appreciate the managerial perspective on the level of desalination plants, which is more concerned operational, technical, and compliance related tasks. One the one hand, a strong state-industry-research collaboration is needed in order to incentive the update of brine management infrastructure and advance the commercial maturity of brine treatment technologies. On the other hand, brine management requires regulatory involvement in order to monitor and improve environmental compliance of desalination plants.

Second, the regulatory and governance based instruments introduced by this paper clearly show that brine management is inherently embedded in wider questions of desalination governance, including the considerations regarding supply security, and the optimal choice of bulk water supply options as well as the cost-benefit calculation for each one. This governance is becoming even more important with the increased complexity of stakeholders and socio-political relationships involved in desalination today as a growing bulk water supply option.

Third, choosing the right options from the brine regulation portfolio is a local task that requires future case-study based investigations. This task should be based on debates within a joint cooperation arena between brine management on a plant level and from a governance perspective. Within this arena, stakeholders can choose adequate options or combination of options. Command-and-control measures represent the baseline for interventions, although they are still lacking or inconsistently applied in many countries. However, there are other or complementary options – e.g. economic and market-based instruments – that can provide opportunities to adjust desalination costs and decrease the cost of technology development. Regulators can choose to work closely with desalination plants to address performance issues and identify environmental remedies.

Finally, public leadership is important as it can alleviate some of the concerns regarding the economic feasibility, risks and liabilities associated with the mitigation of brine's environmental impacts. Using this leadership, stakeholders can cooperate on feasible issues such as innovation and incremental changes towards brine mitigation in desalination plants. At the same time, the regulatory frameworks need to evolve considerably by experimenting with approaches that consider local heterogeneity of supply and actors and the need for multi-sectoral partnerships in addressing brine management issues.

Funding

This report was supported by the NPRP award [NPRP11S-0110- 180248] from the Qatar National Research Fund (a member of The Qatar Foundation).

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.

Acknowledgement

Open Access funding provided by the Qatar National Library.

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