The state of desalination and brine production: A global outlook

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Review

The state of desalination and brine production: A global outlook

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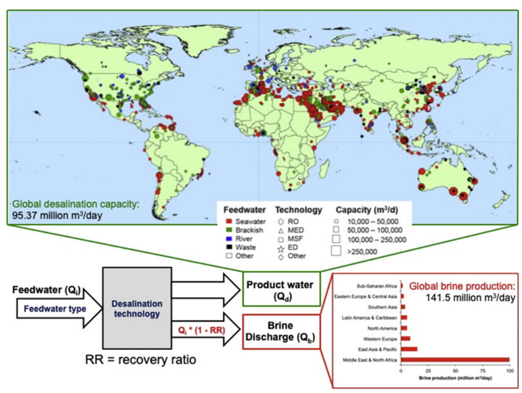
HIGHLIGHTS

- Unconventional water resources are key to support SDG 6 achievement.
- Desalinated water production is 95.37 million m^3/day.
- Brine production and energy consumption are key barriers to desalination expansion.
- Brine production is 141.5 million m^3/day, 50% greater than previous estimates.
- Innovation and developments in brine management and disposal options are required.

GRAPHICAL ABSTRACT



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ABSTRACT

Rising water demands and diminishing water supplies are exacerbating water scarcity in most world regions. Conventional approaches relying on rainfall and river runoff in water scarce areas are no longer sufficient to meet human demands. Unconventional water resources, such as desalinated water, are expected to play a key role in narrowing the water demand-supply gap. Our synthesis of desalination data suggests that there are 15,906 operational desalination plants producing around 95 million m^3/day of desalinated water for human use, of which 48% is produced in the Middle East and North Africa region. A major challenge associated with desalination technologies is the production of a typically hypersaline concentrate (termed 'brine') discharge that requires disposal, which is both costly and associated with negative environmental impacts. Our estimates reveal brine production to be around 142 million m^3/day, approximately 50% greater than previous quantifications. Brine production in Saudi Arabia, UAE, Kuwait and Qatar accounts for 55% of the total global share. Improved brine management strategies are required to limit the negative environmental impacts and reduce the economic cost of disposal, thereby stimulating further developments in desalination facilities to safeguard water supplies for current and future generations.

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Contents

1. Introduction

Rising water demands associated with population growth, increased water consumption per capita and economic growth, coupled with diminishing water supplies due to climate change and contamination, are exacerbating water scarcity in most world regions (Richter et al., 2013; Djuma et al., 2016; Damania et al., 2017). Recent estimates suggest that 40% of the global population faces severe water scarcity, rising to 60% by 2025 (Schewe et al., 2014). Furthermore, 66% of the global population (4 billion) currently lives in conditions of severe water scarcity for at least one month per year (Mekonnen and Hoekstra, 2016). These statistics demonstrate that “conventional” sources of water such as rainfall, snowmelt and river runoff captured in lakes, rivers, and aquifers are no longer sufficient to meet human demands in water-scarce areas. This is in direct conflict with Sustainable Development Goal (SDG) 6, aimed at ensuring the availability of clean water for current and future generations.

Water-scarce countries and communities need a radical re-think of water resource planning and management that includes the creative exploitation of a growing set of viable but unconventional water resources for sector water uses, livelihoods, ecosystems, climate change adaptation, and sustainable development (Qadir, 2018). Whilst water demand mitigation approaches such as water conservation and improved efficiencies can somewhat close the water demand and supply gap, these approaches must be combined with supply enhancement strategies in order to combat water scarcity (Gude, 2017). Such water resources conservation and supply enhancement strategies are already practiced in some water-scarce areas. However, expansion is required, particularly in areas where water scarcity and water quality deterioration is intensifying (van Vliet et al., 2017; Jones and van Vliet, 2018).

Among the water supply enhancement options, desalination of seawater and highly brackish water has received the most consideration and is increasingly seen as a viable option to meet primarily domestic and municipal needs. Desalination is the process of removing salts from water to produce water that meets the quality (salinity) requirements of different human uses (Darre and Toor, 2018). Seawater desalination can extend water supplies beyond what is available from the hydrological cycle, providing an “unlimited”, climate-independent and steady supply of high-quality water (Elimelech and Phillip, 2011). Brackish surface and groundwater desalination offers reductions in the salinity levels of existing terrestrial freshwater resources below sectoral thresholds (Gude, 2017).

The uptake of desalination has been substantial, but limited predominantly to high income countries (e.g. Saudi Arabia, UAE, Kuwait) and small island nations (e.g. Malta, Cyprus) with highly limited ‘conventional’ water resources (e.g. rainfall, snowmelt). However, reductions in the economic cost of desalination associated with technological advances, coupled with rising costs and the diminishing supply and security of “conventional” water resources, have made desalination a cost-competitive and attractive water resources management option around the globe (Ghaffour et al., 2013; Sood and Smakhtin, 2014; Caldera and Breyer, 2017; Darre and Toor, 2018). Nowadays, an estimated 15,906 desalination plants are currently operational, located in 177 countries and territories across all major world regions.

Realising the vast potential of desalinated water remains a challenge due to specific barriers, predominantly associated with the relatively high economic costs and a variety of environmental concerns (e.g. Einav et al., 2002; Roberts et al., 2010; Richter et al., 2013; Darre and Toor, 2018). Continued improvements in membrane technologies, energy recovery systems and coupling desalination plants with renewable energy sources provide opportunities for reducing the economic costs of desalination (Elimelech and Phillip, 2011; Pinto and Marques, 2017; Darre and Toor, 2018), whilst trends towards stricter environmental guidelines and permitting factors may cause the falling trend in desalination costs to slow, level off or reverse (Pinto and Marques, 2017). Regardless, continued reductions in the economic costs of desalination will be required for desalination to be considered a viable option for addressing SDG 6 in low income countries. Detailed evaluations of the challenges and opportunities associated with the economics of desalination are provided by Ghaffour et al. (2013) and Pinto and Marques (2017).

The safe disposal of effluent produced in the desalination process remains a particular concern and a major technical and economic challenge (Roberts et al., 2010). The desalination process separates intake water into two different streams – a freshwater stream (product water) and a concentrate waste stream (Wenten et al., 2017). The salinity of the concentrate stream depends on the salinity of the feedwater. As the vast majority of concentrate is produced from saline water (>95% from SW and BW sources), the term ‘brine’ is used throughout this paper. However, it should be noted that desalination plants operating with low saline feedwater types (e.g. RW, FW) produce concentrate with a lower salinity than typically associated with the term ‘brine’.

A desalination plant water recovery ratio (RR), defined as the volumetric processing efficiency of the purification process (Harvey, 2008), indicates the proportion of intake water that is converted into high quality (low salinity) water for sectoral use. The remaining water (calculated as $(1 - RR)$) is the proportion of intake water being converted into a waste (brine) stream, which requires management. For example, a desalination plant operating with a recovery ratio of 0.4 means that 40% of intake water is converted into product water, and by extension 60% of intake water is converted into brine. The RR of a desalination plant is dependent on and controlled by a number of factors (Xu et al., 2013). Different desalination technologies are associated with variations in RR, with membrane technologies typically associated with a much higher RR than possible with thermal technologies (Xu et al., 2013). The feedwater quality is also important, with it being much more difficult (and expensive) to operate desalination plants at a high level of water recovery when the feedwater salinity is high (Harvey, 2008).

With the aim of providing a global assessment of the research and practice around desalination, the objectives of this study are to: (1) share an insight into the historical development of desalination; (2) provide a state-of-the-art outlook on the status of desalination, considering the number of desalination facilities and their associated treatment capacity with regards to aspects such as geographical distribution, desalination technologies, feedwater types and water uses; and (3) assess brine production from desalination facilities and the management implications of the produced brine. This study therefore seeks to update the literature on the state of desalination in both research and practice, which is outdated. Furthermore, this study makes the first comprehensive quantification of the volume of brine produced by desalination facilities, employing a novel methodology that considers the efficiency of desalination plants based on both their operating technology and the feedwater type.

2. Methodology

2.1. Global status of desalination: research and practice

2.1.1. Desalination in research

A bibliometric analysis was conducted to evaluate the major research trends in the field of desalination. The Science Citation Index Expanded (SCI-EXPANDED) from the Web of Science Core collection was used for the time period 1980 to 2018. This study firstly categorises desalination publications based on major research theme ('technology', 'environment', 'economic and energy' and 'social interests'). Subsequently, considering the 'technology' category, trends in research on specific technologies ('Reverse Osmosis', 'Multi-Effect Distillation', 'Multi-Stage Flash', 'Electrodialysis', 'Emerging' and 'Other') were examined. 'Emerging' refers to technologies largely in the R&D phase (Forward Osmosis, Membrane Distillation and Nanofiltration) whereas older, less prevalent technologies were categorised as 'other' (Humidification-Dehumidification, Solar Stills and Vapour Compression). The precise methodology adopted for the bibliometric study is presented in the Supplementary material.

2.1.2. Desalination in practice

A global database containing information on approximately 20,000 desalination plants (version of 2018) was obtained from Global Water Intelligence (GWI) (https://www.desaldata.com). The database contains information on the plant status, operational year, plant capacity, geographic location (region, country, coordinates), customer type, desalination technology and feedwater type of each individual desalination plant. The precise geographic location of each desalination plant was plotted in ArcGIS using latitude and longitude data. The rest of the data was tabulated using pivot tables in Microsoft Excel to assess statistics of multiple desalination plants per region, technology and other categories. Desalination data (number and capacity of plants) was subsequently analysed at the global, regional and national scale. The specifics within each category by which the global state of desalination was analysed are as follows.

Plant status was categorised as either 1) Online; 2) Presumed online; 3) Construction; 4) Presumed offline; or 5) Offline. In this study, desalination plants were considered 'Operational' if they were classified as either 'Online', 'Presumed online' or 'Construction'. Operational year refers to the year in which the desalination plant opened, assigned unanimously as 2020 for all plants currently in construction. Plant desalination capacity, or the volume of high quality product water produced for human use, is provided in m^3/day for each desalination plant.

Eight geographic regions were identified: 1) East Asia & Pacific; 2) Eastern Europe & Central Asia; 3) Latin America & Caribbean; 4) Middle East & North Africa; 5) North America; 6) Southern Asia; 7) Sub-Saharan Africa; and 8) Western Europe. Country data was used to assign each desalination plant to one of four economic levels based on the 2018 World Bank Income groups, whereby GNI per capita ($) is estimated using the World Bank Atlas method. Countries are assigned to one of four economic classifications: 1) High income (>$12,056 GNI per capita); 2) Upper middle income ($3896 to $12,055); 3) Lower middle income ($966 to $3895); and 4) Low income (<$995).

The sector (or 'customer type') for each desalination plant was separated into six categories: 1) Municipal (including tourist drinking water facilities); 2) Industry; 3) Power stations; 4) Irrigation; 5) Military; and 6) Other. 'Other' comprises uses of Demonstration, Process and Water Injection, which are not considered separately as they account for <0.2% of total desalinated water use.

Feedwater type is separated into six categories in DesalData (2018) expressed in ppm Total Dissolved Solids (TDS): 1) Seawater (SW) [20,000–50,000 ppm TDS]; 2) Brackish water (BW) [3000–20,000 ppm TDS]; 3) River water (RW) [500–3000 ppm TDS]; 4) Pure water (PW) [<500 ppm TDS]; 5) Brine (BR) [>50,000 ppm TDS]; and 6) Wastewater (WW). Despite having a typically high base quality (low salinity), desalination of RW is practiced for a range of different sectoral uses (e.g. drinking water, irrigation) to reduce water salinity below specific sectoral thresholds. PW as a feedwater source is typically used for industrial applications which require very high quality (low salinity) water, such as the pharmaceutical and food production industries.

Desalination technology was separated into seven categories: 1) Reverse Osmosis (RO); 2) Multi-Stage Flash (MSF); 3) Multi-Effect Distillation (MED); 4) Nanofiltration (NF); 5) Electrodialysis/Electrodialysis Reversal (ED); (6) Electrodeionization (EDI); and 7) Other. 'Other' included a variety of technologies such as 1) Forward Osmosis (FO); 2) Hybrid (HYB); 3) Membrane distillation (MD); 4) Vapour compression (VP); and 5) Unknown. As the technologies grouped together under the 'Other' category contribute a total of <1% of the total desalinated water produced, these technologies were not considered individually.

2.2. Brine production

The volume of brine produced was determined at each individual (operational) desalination plant using three factors contained in DesalData (2018) - feedwater type, desalination technology and treatment capacity (m^3/day). We consider the water recovery ratios associated with different feedwater-desalination technology combinations and calculate the brine production based on this recovery ratio and the plant capacity using Eq. (1).

$$Qb = \frac{Qd}{RR} * (1 - RR) \tag{1}$$

whereby Qb is the volume of brine produced (m^3/day); Qd is the desalination plant treatment capacity (m^3/day) and; RR is the recovery ratio.

In total, 41 different feedwater type and desalination technology combinations are currently operational. The recovery ratio associated with each of these feedwater-technology combinations was determined using two methods. Firstly, a literature study was conducted in order to identify values of recovery ratios (or % water efficiency) for different technologies and feedwater types reported in existing studies. When recovery ratios were expressed as a range, the midpoint was used. In total, 89 recovery ratios were found in the literature across a range of feedwater-technology combinations. Secondly, influent and effluent salinity data from individual desalination plants operating with membrane technologies was used to estimate recovery ratios using Eqs. (2) and (3) (Bashitialshaaer et al., 2009).

$$Sb = \frac{Sf}{1 - RR} \tag{2}$$

$$RR = 1 - \frac{Sf}{Sb} \tag{3}$$

whereby Sb is the brine salinity and Sf is the feedwater salinity, with both salinities expressed in the same units (e.g. mS/cm for EC, mg/l for TDS).

We obtained 30 additional recovery ratios using this method, which were combined with recovery ratios identified in the literature to produce 119 records. From this, average recovery ratios could be identified for 18 of the 41 technology-feedwater. Whilst this coverage might seem low, desalination-technology combinations are not all equally prevalent in terms of number of plants and desalination capacity. These 14 combinations account for >80% of the total desalinated water produced globally, with the top three combinations (seawater (SW)-RO, brackish water (BW)-RO and SW-MSF) accounting for 70% of the produced desalinated water alone. In order to determine recovery ratios for the remaining feedwater-technology combinations, a number of assumptions and estimations were made (Table 1).

Latitude and longitude data was used to calculate the distance of each desalination plant from the nearest coastline using the Spatial Analyst tool in ArcGIS. Combined with the estimated brine production for each desalination plant, we calculated the volume of brine produced at different distances from the coastline to consider the implications for brine management.

3. Results

3.1. Research trends in desalination

Trends in the research history of desalination are displayed in Fig. 1. Approximately 16,500 publications were found to have been produced on the topic of desalination since 1980. Research in desalination has grown exponentially, with the total number of publications approximately doubling with each five-year period (e.g. ~5000 in 2010 to ~11,000 in 2015). The large majority of publications focus on technological aspects of desalination (e.g. 75% in 2005). As such, desalination literature focusing on technological aspects has driven the overall trend in desalination research. Whilst the proportion of desalination literature covering technological aspects is still high (72%), there has been an emergence of literature covering alternative aspects of desalination, particularly related to economics and energy and environmental concerns. The number of publications considering economic aspects of desalination has increased dramatically in recent decades, from <400 in 2000 to >5000 in 2018. Historically, the environmental impacts of desalination were severely neglected, with just 118 publications before 2000. However, literature published in this category is now increasing at the fastest rate, with an additional ~2000 publications since 2000. The number of publications addressing socio-political aspects of desalination is relatively low. Desalination is not typically associated with social opposition and conflict associated with other water supply schemes such as river regulation (e.g. dam buildings) and water transfers (March et al., 2014), which may in part explain the lack of publications. Furthermore, desalination operations are not typically associated with the gender issues and community-based factors associated with other unconventional water resources, such as fog water harvesting (Qadir et al., 2018; Lucier and Qadir, 2018). However, desalinated operations are associated with some important (and under-researched) policy-related aspects, such as the lack of specific water standards for desalinated water for both the municipal (Chen et al., 2015) and agricultural sectors (Martinez-Alvarez et al., 2016). As desalination continues to become a more prevalent water resources management technology in the future, the number of publications across all categories, and especially environmental and socio-political themes, is expected to increase rapidly.

Publications addressing technological aspects have dominated the research history of desalination (Fig. 1). Fig. 2 further explores this trend by categorising 'technological' publications by specific technology. RO is the most researched technology throughout the entire time period, with the number of publications approximately doubling each five-year period. Research into 'emerging' technologies (FO, MD and NF) is increasing at the most rapid pace with increasing recognisation of their potential advantages over existing commercial technologies. These include factors such as operating at higher water recovery ratios and requiring less and/or sustainable energy (Subramani and Jacangelo, 2015). Thermal technologies (MED and MSF), despite accounting for a significant share in the amount of desalinated water produced, have received comparatively little attention in recent literature. Whilst publications addressing MSF and MED accounted for a significant proportion of research in the 1980s and 1990s, they are now the overall least researched technologies. Concerns over the energy costs, efficiency and environmental impacts of thermal processes, and the development of more efficient membrane technologies and techniques (particularly RO), likely explain this trend.

3.2. Global state of desalination

There are 15,906 operational desalination plants with a total desalination capacity of approximately 95.37 million m^3/day (34.81 billion m^3/year), constituting 81% and 93% of the total number and capacity of desalination plants ever built respectively (Fig. 3a). Early desalination plants predominantly utilised thermal technologies, located in oil-rich but water scarce regions, especially in the Middle East. For example, prior to the 1980s, 84% of all global desalinated water was being produced by the two major thermal technologies (MSF, MED). The rise in the use of membrane technologies post-1980, in particular RO, gradually shifted the dominance away from thermal technologies. In 2000, the volumes of desalinated water produced by thermal technologies (dominated by MSF) and RO were approximately equal at 11.6 million m^3/day and 11.4 m^3/day respectively, together accounting for 93% of the total volume of desalinated water produced (Fig. 3b). Since 2000, both the number and capacity of RO plants has risen exponentially, whilst thermal technologies have only experienced marginal increases (Fig. 3b). The current production of desalinated water from reverse osmosis now stands at 65.5 million m^3/day, accounting for 69% of the volume of desalinated water produced.

The spatial distribution, size and customer type of desalination facilities (>1000 m^3/day) are displayed in Fig. 4. Large numbers of desalination facilities are located in the United States, China and Australia and across the regions of Europe, North Africa and the Middle East. Relatively few desalination facilities are located in South America and Africa, with existing facilities predominantly designed to produce desalinated water for the industrial sector. Desalination plants globally are concentrated on and around the coastline, with coastal desalination plants also tending to be larger than inland desalination plants. Plants producing municipal water are located worldwide, but are particularly dominant in the Middle East & North Africa region. Comparatively,

Table 1
Assumptions and estimations used determining the recovery ratios of feedwater-technology combinations used in operational desalination plants.

	Assumption
1	When brackish water (BW) recovery is known, the water recovery ratio of brine (BR) (TDS >50,000 ppm), seawater (SW) (TDS 20,000–50,000 ppm), river water (RW) (TDS 500–3000 ppm) and pure water (PW) (TDS <500 ppm) is assumed to be the 95th, 90th, 10th and 5th percentiles of brackish water technologies respectively.
2	When brackish water (BW) recovery is unknown but seawater water (SW) recovery is known, the water recovery ratio of brine water (BR), brackish water (BW), river water (RW) and pure water (PW) is assumed to be the 90th, 25th, 10th and 5th percentiles of seawater technologies respectively.
3	The recovery rate of wastewater (WW) for each technology is assumed to be equal to the recovery rate of brackish water for the same technology.
	Estimation
1	Other technologies cover a range of different technologies. An estimated 40% water recovery ratio was assigned for highly saline water (above 20,000 ppm) and 60% recovery for brackish and slightly saline water sources (below 20,000 ppm).

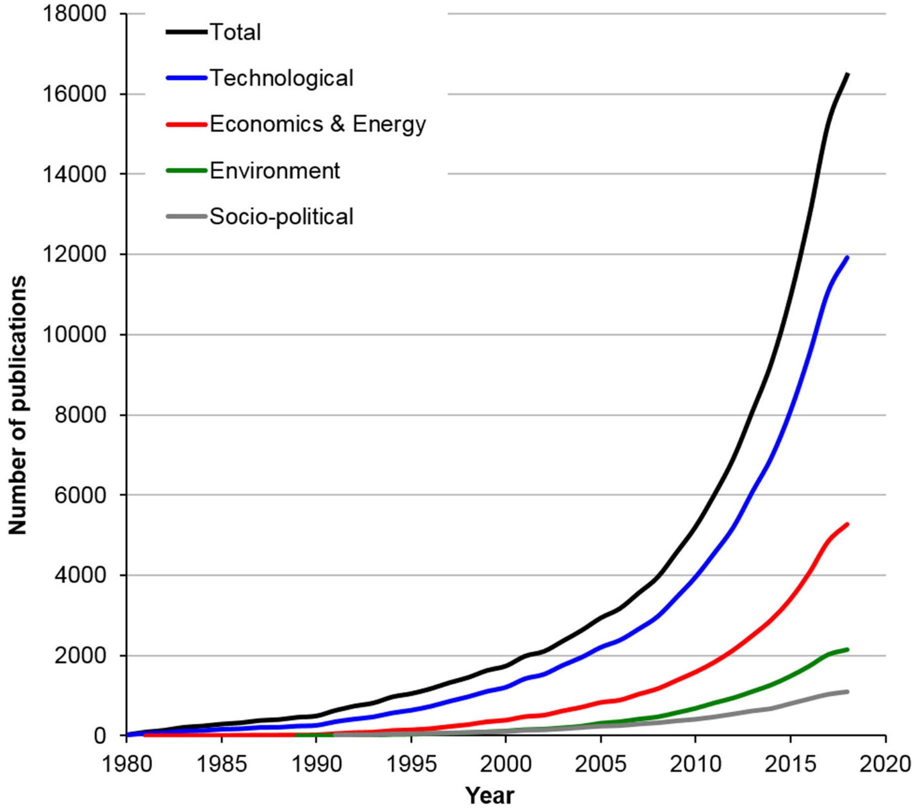

Fig. 1. Number of desalination publications by categorisation (total, technical, social, environment, energy & economic).

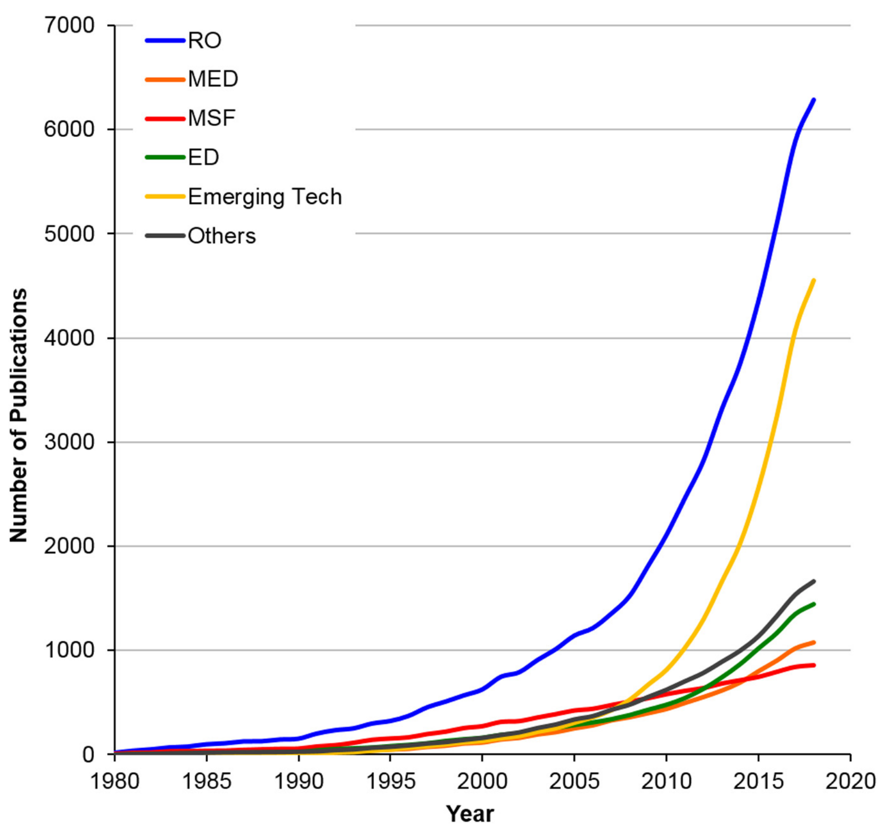

Fig. 2. Number of publications by type of desalination technology (Reverse Osmosis [RO], Multi-Effect Distillation [MED], Multi-Stage Flash [MSF], Electrodialysis [ED]), emerging technologies (Nanofiltration [NF], Forward Osmosis [FO] and Membrane Distillation [MD]) and other (Humidification-Dehumidification [HDH], Solar Stills [SS] and Vapour Compression [VC]).

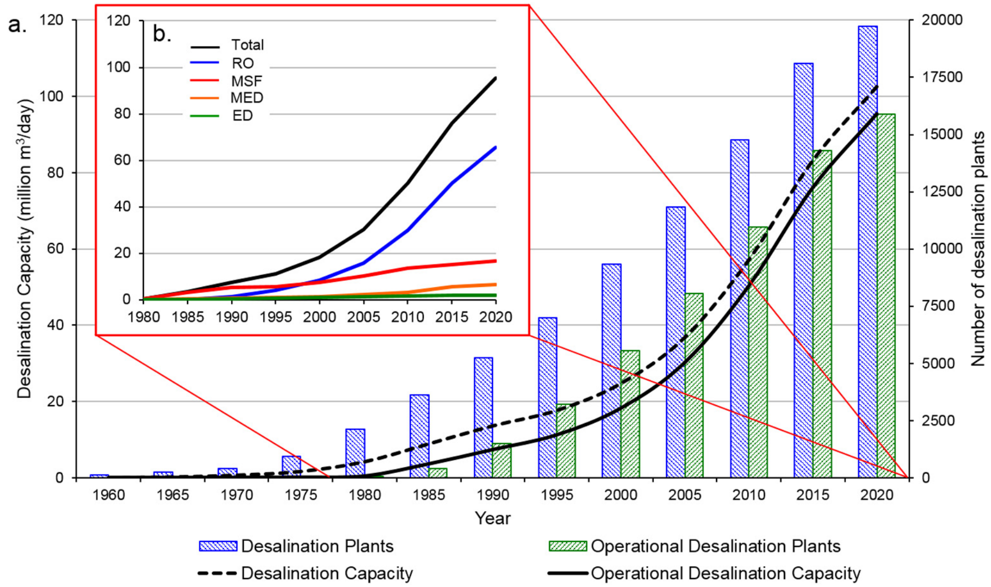

Fig. 3. Trends in global desalination by (a) number and capacity of total and operational desalination facilities and (b) operational capacity by desalination technology.

there is a far greater proportion of desalination plants producing water for non-municipal purposes in North America, Western Europe and East Asia and Pacific regions, whereby generation of water for industrial and power applications also command large market shares (Fig. 4).

The number and capacity of desalination plants by geographic region, country income level and sectoral use of desalinated water (Table 2) reveal that almost half of the global desalination capacity is located in the Middle East and North Africa region (48%), with Saudi Arabia (15.5%), the United Arab Emirates (10.1%) and Kuwait (3.7%) being both the major producers in the region and globally. East Asia and Pacific and North America regions produce 18.4% and 11.9% of the global desalinated water, primarily due to large capacities in China (7.5%) and the USA (11.2%). The widespread use of desalination in Spain (5.7%) accounts for over half of the total desalination in Western Europe (9.2%). The global share in desalination capacity is lower for Southern Asia (3.1%), Eastern Europe and Central Asia (2.4%) and Sub-Saharan Africa (1.9%), where desalination is primarily restricted to small facilities for private and industrial applications. The majority of desalination facilities are located in high income countries (67%), accounting for the majority of the global desalination capacity (71%). Conversely, very few desalination plants are located in low income countries, which contribute a negligible proportion (<0.1%) of the global desalination capacity.

Whilst almost half of the total number of desalination plants produce water for the industrial sector, the municipal sector is the largest user of desalinated water in terms of capacity. 62.3% of desalinated water is produced for human consumption (municipal sector), compared to 30.2% for industrial applications. This pattern occurs due to the (typically) smaller capacity of industrial desalination facilities, which average 3712 m^3/day, compared to desalination plants producing municipal water that average 12,126 m^3/day. Whilst the municipal and industrial sectors account for the vast majority of the global desalination capacity, the power (4.8%) and irrigation (1.8%) sectors consume a small but significant proportion of produced desalinated water.

Of the desalination technologies, RO is by far the most dominant process, accounting for 84% of the total number of operational desalination plants, producing 69% (65.5 million m^3/day) of the total global desalinated water (Fig. 5a). The two major thermal technologies, MSF and

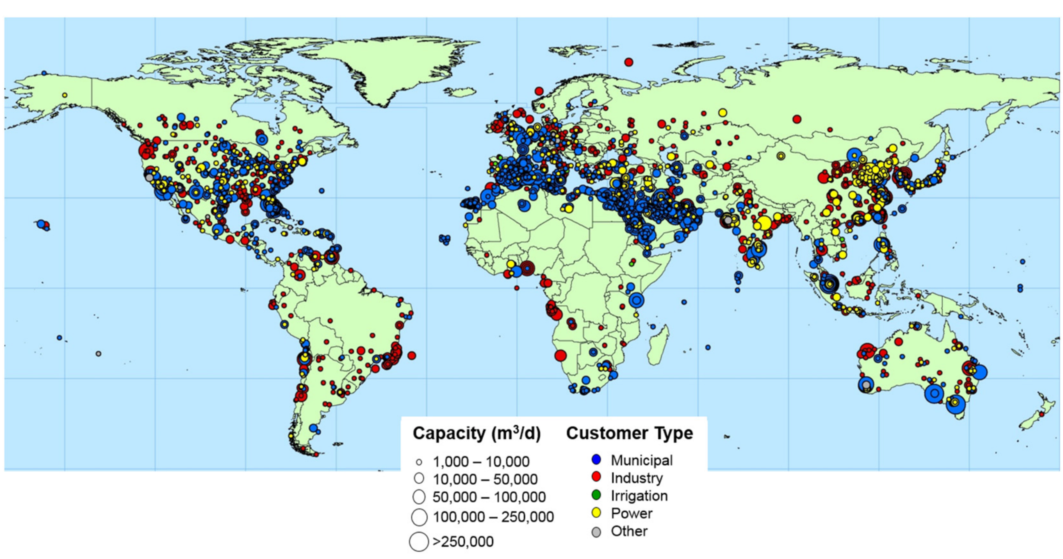

Fig. 4. Global distribution of operational desalination facilities and capacities (>1000 m^3/day) by sector user of produced water.

Table 2
Number, capacity and global share of operational desalination plants by region, country income level and sector use.

	Number of desalination plants	Desalination capacity	
		(million m^3/day)	(%)
Global	15,906	95.37	100
Geographic region			
Middle East and North Africa	4826	45.32	47.5
East Asia and Pacific	3505	17.52	18.4
North America	2341	11.34	11.9
Western Europe	2337	8.75	9.2
Latin America and Caribbean	1373	5.46	5.7
Southern Asia	655	2.94	3.1
Eastern Europe and Central Asia	566	2.26	2.4
Sub-Saharan Africa	303	1.78	1.9
Income level			
High	10,684	67.24	70.5
Upper middle	3075	19.16	20.1
Lower middle	2056	8.88	9.3
Low	53	0.04	0.0
Sector use			
Municipal	6055	59.39	62.3
Industry	7757	28.80	30.2
Power	1096	4.56	4.8
Irrigation	395	1.69	1.8
Military	412	0.59	0.6
Other	191	0.90	0.4

MED, despite being relatively few in number, produce the majority of the remaining desalinated water, with market shares of 18% and 7% respectively (Fig. 5a). In total, these three technologies account for 94% of the total desalinated water produced, with plants using NF (3%), ED (2%) and EDI (<1%) technologies producing smaller volume of desalinated water (Fig. 5a).

In terms of feedwater source, which is indicative of feedwater quality, SW desalination accounts for 61% of produced water (Fig. 5b). Desalination of BW and RW produce the next largest volumes of desalinated water, with market shares of 21% and 8% respectively (Fig. 5b). In total, these three sources account for 90% of the total volume of desalinated water produced, with the remainder being produced from WW (6%), PW (4%) and BR (<1%).

Whilst Fig. 5 clearly demonstrates the relative dominance of RO, MSF and MED in terms of desalination technology, and SW, BW and RW in terms of feedwater source, the combination of both these factors is important. Desalination technologies can be considered semi-specialised in that they operate most efficiently when using particular source water types, or that their economic viability is dependent on source water type, and hence some feedwater-technology combinations are significantly more prevalent than others.

RO is a process that is economically viable across a range of feedwater types, and hence the feedwater type used is dependent on local availability (Fig. 5). 50% and 27% of the desalinated water that is produced from RO desalination plants, accounting for 34% and 19% of the global desalination capacity, originates from SW and BW water, respectively. RO of RW (7%) and WW (5%) also contributes a significant proportion of the global desalination capacity. Comparatively, thermal technologies are used almost exclusively for low quality (highly saline) feedwater types. 96% of MSF plants and 80% of MED plants use feedwater with >20,000 ppm TDS, the vast majority of which use sea water. SW accounts for 99.9% and 92% of the total volume of desalinated water produced by MSF and MED respectively, representing global market shares of 18% and 6%. Conversely, plants operating with ED as the desalination technology typically require water of a higher base quality (lower salinity). 60% and 20% of the desalinated water produced by ED originates as BW and RW respectively, contributing a small but significant proportion of the total global volume of desalinated water. In total, eight feedwater-technology combinations (SW-RO, BW-RO, SW–MSF, SW–MED, RW-RO, WW-RO, BW-ED, RW-ED) are responsible for the production of over 90% of the global desalinated water.

Fig. 6 reveals the spatial distribution and size of large (>10,000 m^3/day) desalination plants operating under different feedwater-technology combinations. Thermal desalination technologies (MED, MSF) operating with sea water as the feedwater type are dominant in the Middle East, with the exception of a large number of BW-RO plants located in inland Saudi Arabia. Outside of this region, very few large thermal plants exist, with RO being the dominant technology across a range of feedwater types. For example, large desalination plants in Australia operate almost exclusively using RO technology, but with a variety of feedwater types including SW, BW and WW. RO is also the dominant technology across the United States, although the vast majority of desalination plants operate using BW and RW, with only a small number of seawater plants located in California and Florida. Western Europe, and in particular Spain, is dominated by RO using a variety of feedwater sources, although there is also a significant number of desalination plants operating using alternative technologies such as ED and NF. Lastly, SW-RO dominates desalination in the coastal areas of Asia, although a significant number of BW- and RW-RO plants are located inland.

3.3. Brine production

The water recovery efficiency of desalination operations depends on both the type of desalination technology and the quality of feedwater used, and therefore both of these factors must be considered when quantifying brine production (Xu et al., 2013). Table 3 displays the water recovery ratios associated with the major feedwater-technology combinations in operation.

For all technologies, the recovery ratio increases as the feedwater quality increases (salinity decreases), with BR associated with the lowest water recovery ratios and PW associated with the highest recovery ratios. Feedwater type is a substantial determinant of the recovery ratio associated with a particular technology. For example, SW-RO operates at a substantially lower recovery ratio (0.42) compared to BW-RO (0.65) and RW-RO (0.85). Similarly, BW-NF (0.83) is substantially more efficient than SW-NF (0.69). Individual desalination technologies are also associated with vastly different recovery ratios. Thermal technologies (e.g. MSF, MED) are typically associated with much lower recovery ratios than membrane technologies (e.g. RO, NF). For example, the recovery ratio of MSF across all feedwater types is approximately half that of RO. The water recovery ratio of other membrane technologies (NF, ED, EDI, EDR) is substantially higher than RO across all feedwater types.

Energy requirements, and hence economic costs, vary depending on feedwater type. For membrane technologies, low salinity feedwater types (e.g. RW) require less applied pressure than high salinity feedwater types (e.g. SW) for desalination, causing lower energy consumption per unit water produced (Ghaffour et al., 2013). This results in substantially lower investment costs (Ghaffour et al., 2013). However, highly efficient membrane technologies are rarely used for desalination of highly saline feedwater types, with a total of just 0.01% desalinated water being produced by SW or BR in combination with NF, ED, EDI and EDR. For highly saline feedwater types, RO and thermal processes (e.g. MSF, MED) dominate. Whilst thermal technologies (particularly MED) are associated with higher energy consumption, the economic cost of desalting SW is comparable to RO due to lower investment costs (Ghaffour et al., 2013).

Current global brine production stands at 141.5 million m^3/day, totaling 51.7 billion m^3/year (Table 4). This value is approximately 50% greater than the total volume of desalinated water produced globally. Global brine production is concentrated in the Middle East and North Africa, which produces almost 100 million m^3/day of brine, accounting for 70.3% of global brine production. This value is approximately double the volume of desalinated water produced, indicating that desalination plants in this region operate at an (very low) average water recovery

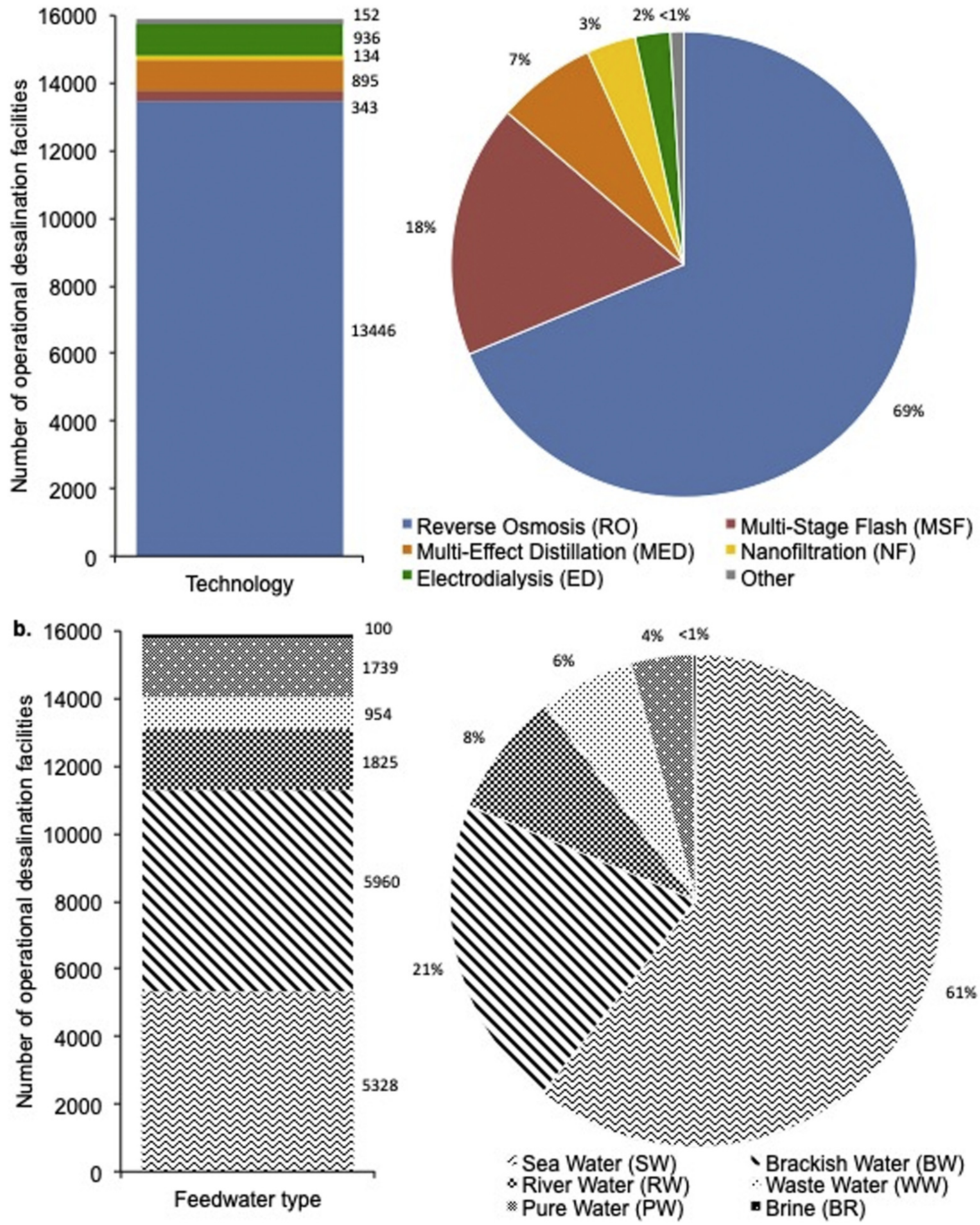

Fig. 5. Number and capacity of operational desalination facilities by (a) technology and (b) feedwater type.

ratio of 0.25. Comparatively, all other regions produce substantially lower volumes of brine, with East Asia and Pacific (10.5%), Western Europe (5.9%) and North America (3.9%) having the next largest shares. Interestingly, these regions produce a substantially lower volume of brine than the amount of desalinated water they produce, indicating that recovery ratios are generally high. This is particularly apparent for North America, which produces a substantially lower volume of brine than it does desalinated water, suggesting that desalination facilities operate at an average recovery ratio of 0.75. In other geographical regions, brine production is approximately equivalent to desalinated water production (i.e. RR = 0.5).

As with desalinated water production, high income countries produce the vast majority of global brine (77.9%). It should be noted that 'high income' includes both countries from both highly developed world regions (e.g. North America, Western Europe), whose brine production tends to be smaller relative to the desalinated water production, and the oil-rich Gulf nations who typically employ thermal desalination technologies with low recovery ratios, hence high brine production. For example, Saudi Arabia alone produces 31.53 million m^3/day brine, accounting for 22.2% of the global share. The next three largest producers of brine are also oil-rich countries, with the UAE, Kuwait and Qatar having 20.2%, 6.6% and 5.8% shares in global brine production respectively. Together, these four nations produce 32% of global desalinated water and 55% of the total brine. Comparatively, the USA produces 10.91 million m^3/day of desalinated water (11.4% global share) but produces just 5.28 million m^3/day of brine (3.7% global share). Upper middle income, lower middle income and low income countries tend to produce quantities of brine similar to that of their respective desalination capacities.

Water produced for the municipal sector is by far the largest producer of both desalinated water and brine, although the quantity of brine produced is much greater. This pattern arises primarily due to the vast quantity of desalinated drinking water produced for the Gulf nations, whereby thermal technologies operating with SW dominate. Both the industrial and agricultural sectors produce lower quantities of brine than desalinated water, indicating desalinated water for these sectors is produced by feedwater-technology combinations with higher water recovery ratios. This is particularly pronounced in the agricultural

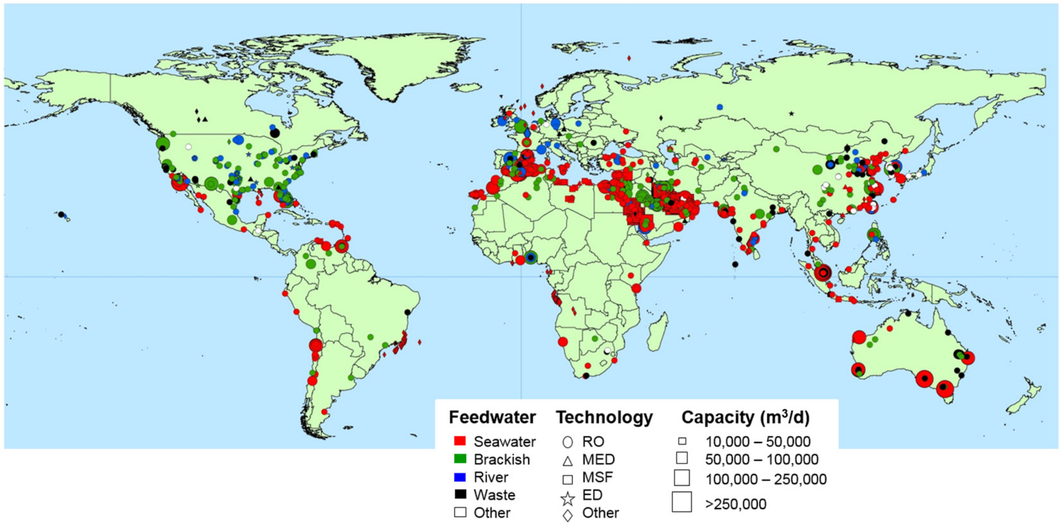

Fig. 6. Global distribution of large desalination plants by capacity, feedwater type and desalination technology.

sector due to the dominance of high-quality (low salinity) feedwater sources used for producing desalinated water for use in agriculture sector.

The geographical location of brine production influences the economic and technical viability of different methods of brine disposal (Arnal et al., 2005). Desalination plants located near the shoreline often discharge untreated brine directly into saline surface water bodies (e.g. oceans, seas) (Arnal et al., 2005). As almost half of brine is produced within 1 km of the coastline, rising to almost 80% produced within 10 km, ocean disposal is assumed to be the dominant brine disposal method worldwide (Table 5). The countries producing large volumes of brine (>1 million m^3/day) in coastal locations are largely concentrated in the Middle East and North Africa (e.g. UAE, Saudi Arabia) and South-East Asia (China, India), and in the USA and Australia (Fig. 7a). The volume of brine produced in many of these countries far exceeds 1 million m^3/day, particularly in the Middle East. In this region, the four largest brine producers (UAE, Saudi Arabia, Qatar, Kuwait) account for 72.2 million m^3/day of the brine that is produced within 10 km of the coastline.

Whilst brine disposal into saline surface water bodies raises some important environmental concerns, this option is extremely economical (Arnal et al., 2005). However, this option is often not available for inland desalination plants, which account for a smaller yet significant proportion of the volume of brine being produced. Almost 22 million m^3/day of brine is produced at a distance of >50 km from the nearest coastline (Table 5). Despite the large volume of brine produced inland, very few economically viable and environmentally sound brine management options exist (Arnal et al., 2005). Brine produced inland poses an important problem for many countries located in all world regions, with 64 countries producing >10,000 m^3/day of brine in inland locations (Fig. 7b). Whereas the volume of brine produced in coastal locations is largely concentrated in the Middle East, inland brine production is a particular issue in other locations such as China (3.82 million m^3/day), USA (2.42 million m^3/day) and Spain (1.01 million m^3/day) (Fig. 7b).

Whilst Fig. 5 considered the production of desalinated water by technology and feedwater type separately, Fig. 8a combines these two elements, displaying the 6 major feedwater-technology combinations by volume of desalinated water produced. As displayed in Fig. 5, RO is

Table 3
Recovery ratio of different feedwater-technology combinations producing desalinated water.

Feedwater type	Technology							
	RO	MSF	MED	NF	ED	EDI	EDR	Other
Seawater (SW)	0.42	0.22	0.25	0.69	0.86	0.90		0.40
Brackish (BW)	0.65	0.33	0.34	0.83	0.90	0.97	0.90	0.60
River (RW)	0.81		0.35	0.86	0.90	0.97	0.96	0.60
Pure (PW)[a]	0.86	0.35		0.89	0.90	0.97	0.96	0.60
Brine (BR)	0.19	0.09	0.12		0.85			0.40
Wastewater (WW)[b]	0.65	0.33	0.34	0.83	0.90	0.97		0.60

Based on data from: Ahmed et al. (2001), Allison (1993), Almulla et al. (2003), Bashitialshaaer et al. (2007), Belatoui et al. (2017), Bleninger et al. (2010), Costa and De Pinho (2006), DesalData (2018), Efraty and Gal (2012), Fernández-Torquemada et al. (2005), Garcia et al. (2011), Gomez and Cath (2011), Greenlee et al. (2009), Hajbi et al. (2010), Harvey (2008), Kelkar et al. (2003), Khawaji et al. (2007), Korngold et al. (2009), Kurihara et al. (2001), Macedonio and Drioli (2008), Mohamed et al. (2005), Mohsen and Gammoh (2010), Pilat (2001), Pearce et al. (2004), Qiu and Davies (2012), Qurie et al. (2013), Singh (2009), Stover (2013), Valero and Arbós (2010), Von Gottberg et al. (2005), Voutchkov (2011), Wilf and Klinko (2001), Xu et al. (2013), Younos (2005) and Zhou et al. (2015).

[a] PW refers to water of a high base quality (low salinity), but that is desalinated primarily for industrial applications requiring very low salinity water (e.g. food processing, pharmaceutical manufacturing).

[b] WW refers to reject water from municipal and industrial sources undergoing desalination in specific WW desalination facilities.

Table 4
Brine production and share of global total by region, income level and sector use.

	Brine production	
	(million m^3/day)	(%)
Global	141.5	100
Geographic region		
Middle East & North Africa	99.4	70.3
East Asia & Pacific	14.9	10.5
North America	5.6	3.9
Western Europe	8.4	5.9
Latin America & Caribbean	5.6	3.9
Southern Asia	3.7	2.6
Eastern Europe & Central Asia	2.5	1.8
Sub-Saharan Africa	1.5	1.0
Income level		
High	110.2	77.9
Upper middle	20.7	14.6
Lower middle	10.5	7.4
Low	0.03	0.0
Sector use		
Municipal	106.5	75.2
Industry	27.4	19.3
Power stations	5.8	4.1
Irrigation	1.1	0.8
Military	0.5	0.3
Other	0.3	0.2

Table 5
Brine production and share of global total by distance to coastline.

Distance to coastline	Brine production	
	(million m^3/day)	(%)
<1 km	69.0	48.8
1 km–10 km	43.2	30.5
10 km–50 km	7.3	5.2
>50 km	22.0	15.5

the dominant desalination technology, with significant additional contributions from MSF and MED technologies (Fig. 8a). However, large volumes of desalination water are produced by RO from a variety of feedwater sources (SW, BW, RW and WW), whilst the two thermal technologies almost exclusively use SW. The share in brine production from each desalination feedwater-technology combination is displayed in Fig. 8b. The vast majority of brine, 124.5 million m^3/day (87.9%), comes from SW desalination plants. Comparatively, brine production from desalination plants operating with other feedwater types is much smaller, with BW, RW and WW plants producing 10.23 (7.2%), 1.80 (1.3%) and 3.57 (2.5%) million m^3/day, respectively. Individually, SW-MSF accounts for the largest volume of brine production (43%), with SW-RO (31%), SW-MED (12%) and BW-RO (7%) accounting for the vast majority in the remainder of the global share (Fig. 8b).

Clear discrepancies exist when comparing the volume of desalinated water produced to the volume of brine water produced by different feedwater-technology combinations (Fig. 8c). These differences are directly related to the different water recovery ratios associated with desalination plants operating with different feedwater-technology combinations. The greater the volumetric processing efficiency of the desalination process, the smaller the proportion of brine produced relative to the volume of desalinated water produced. For example, RW-RO operates at very high water recovery ratios, therefore producing 6.8 million m^3/day of desalinated water (7.1% global share) whilst producing just 1.6 million m^3/day of brine (1.1% global share). Conversely, whilst SW-MSF desalination plants produce 16.7 million m^3/day (17.6% global share) of desalinated water, brine production totals 60.1 million m^3/day (43% global share).

4. Discussion

Owing to recent, rapid developments in desalination research, the last comprehensive assessment (Tanaka and Ho, 2011) available in the academic literature is outdated. This study presents statistical analysis of the scientific literature covering an array of desalination topics since 1980, addressing a diverse range of social and technical aspects with respect to publication date, revealing patterns in publishing trends. Our findings suggest that research in desalination has increased exponentially over the last 40 years, coinciding with the more widespread recognition of the value of these technologies for water resources management. Research has particularly considered the technological aspects of desalination, with the vast number of publications addressing RO and novel ('emerging') techniques that can produce desalinated water at lower economic costs and with less negative environmental implications (Arnal et al., 2005). Developments in novel desalination techniques, membrane materials and modules dominate the technological literature (Greenlee et al., 2009). Publications addressing economic, environmental and socio-political aspects of desalination are rapidly increasing with expansions in desalination. In particular, the environmental impacts associated with hypersaline brine discharges from desalination plants have received increased attention in recent research, coinciding with water scarcity intensification and the resultant expansion in desalination operations in the USA, Europe and Australia (Roberts et al., 2010).

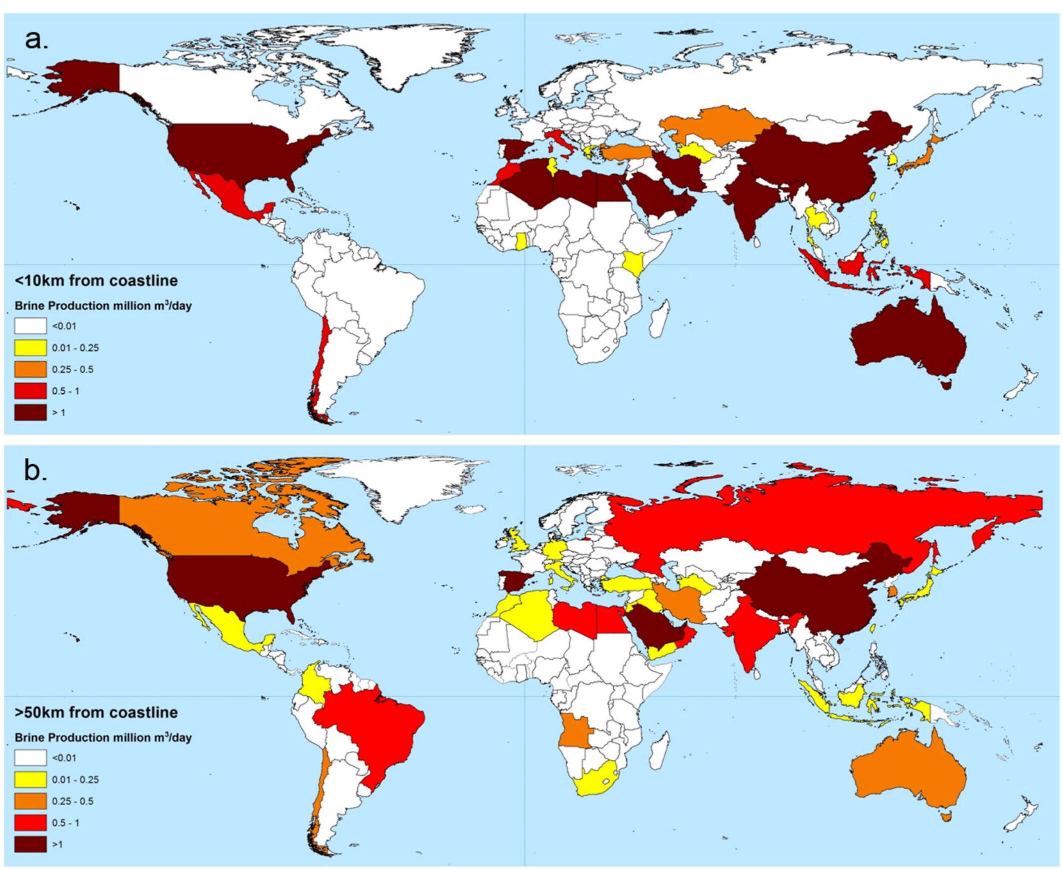

Fig. 7. Volume of brine produced per country at a distance of a) <10 km and b) >50 km from the coastline.

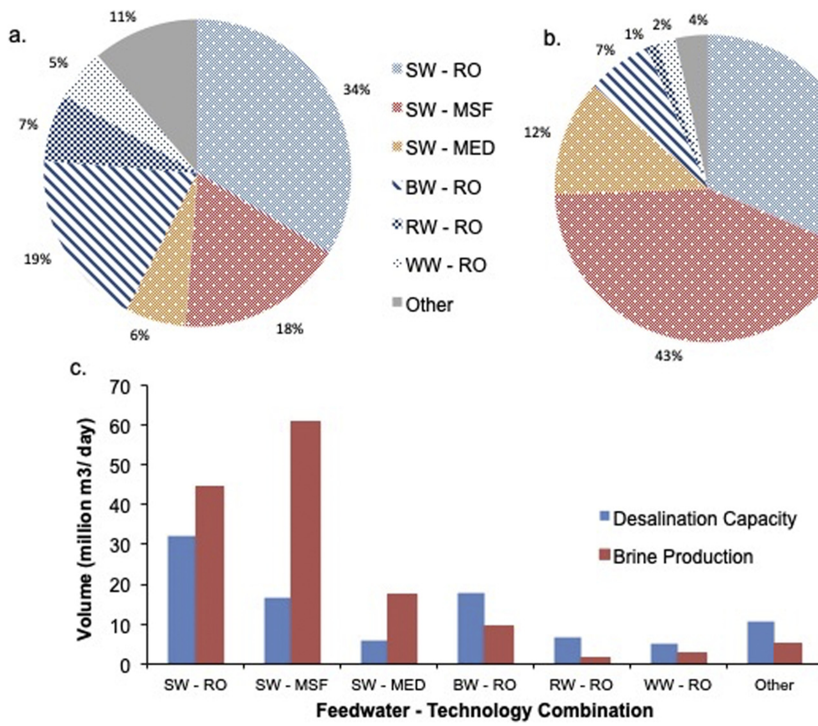

Fig. 8. Major desalination feedwater-technology combinations by (a) global share in the desalinated water production (%), (b) global share in brine production (%) and (c) total desalination capacity and volume of brine produced (million m^3/day).

With regards to desalination in practice, the current state-of-the-art in the global desalination situation in existing academic literature is either a) severely outdated or b) derived from incomplete sources. This study uses the largest and the most complete desalination dataset available (DesalData, 2018) to comprehensively analyse the global state of desalination with respect to desalination geographical distribution, sector use, technology and feedwater type. Our findings demonstrate that the global desalination capacity far exceeds values frequently cited in the literature, due to both the vast expansion in desalination operations that have taken place across the globe in the last decade and the coverage of the dataset used. The major uncertainty related to these results is due to the completeness of the desalination database, which was minimised by using a very high-quality dataset (DesalData, 2018).

Accurate quantifications of the volume of desalinated water produced for human use at different spatial scales is associated with a range of management implications. For example, in order to more representatively assess the degree of water scarcity, unconventional water resources and management practices must be included (Vanham et al., 2018; Jones and van Vliet, 2018). The exclusion of desalination from quantifications of water scarcity is identified as a major shortcoming of SDG 6.4.2 (Vanham et al., 2018), and hence accurate data on the volume of desalinated water produced is important for assessing the actual status of water availability. This is particularly important as water scarcity has been identified as a key challenge, which is expected to intensify in the future (Richter et al., 2013).

The importance of desalination for alleviating water scarcity and safeguarding water resources for human use should not be underestimated. Based on FAO AQUASTAT water withdrawal data (http://www.fao.org/nr/water/aquastat/water_res/index.stm) and desalination capacity data from DesalData (2018), eight countries produce more desalination water than they withdraw for human use (The Maldives, Singapore, Qatar, Malta, Antigua and Barbuda, Kuwait, The Bahamas and Bahrain). A further six countries meet over 50% of their water withdrawals through desalination (Equatorial Guinea, UAE, Seychelles, Cape Verde, Oman and Barbados). As demonstrated through these countries, desalination is an essential technology in the Middle East and for small island nations which typically lack renewable water resources.

Whilst there are demonstrated benefits from desalinated water, there are concerns related to the volume and salinity of brine produced as a waste of desalination process. It poses some of the biggest constraints to more widespread development of desalination operations, in addition to representing a significant proportion of the economic costs of the process (5–33%) (Ahmed et al., 2001). Therefore, quantifying the volume of brine produced by desalination plants operating with different feedwater types and technologies is essential for considering the potential environmental and economic costs associated with desalination.

The volume of brine being produced from desalination plants globally is largely unknown, with the only estimates available in the literature assuming that the volume of brine is equivalent to the volume of desalinated water produced (Liu et al., 2016; Akinaga et al., 2018), regardless of the feedwater type or desalination technology. Our study considers the influence of both feedwater type and desalination technology on the water recovery ratio, deriving values for the vast majority of feedwater-technology combinations producing desalinated water. This information is applied with respect to the treatment capacity of individual desalination plant to determine the volume of brine production, thus representing a first comprehensive attempt to accurately quantify brine production.

Our findings also indicate that the volume of brine produced far exceeds the volume of desalinated water produced (by ~50%), and hence that the current quantifications of volume of brine produced are gross underestimations. However, the uncertainties associated with our method should be considered. In our brine assessment methodology, we assigned recovery ratios based solely on the feedwater type and desalination technology producing desalinated water at each plant, with no consideration of local conditions in these plants. Evidence suggests that site-specific local conditions may also influence a desalination plants recovery ratio (Xu et al., 2013). For example, the effect of variations in feedwater salinity within each 'feedwater type' categorisation (e.g. seawater) on the recovery ratio is overlooked as a result of using the average. Other factors that may influence the specific recovery of each individual desalination plant include specific plant design (e.g. type of membrane used in desalination process), product water quality requirements (e.g. salinity), energy source and brine disposal methodology. Furthermore, whilst desalination plant recovery ratios are available in the literature, the number of values used for determining recovery ratios for some feedwater-technology combinations was low. For some feedwater-technology combinations, no values were found in the literature, and therefore a number of assumptions and estimations had to be made (Table 1). This uncertainty was minimised as recovery ratios were found in the literature for all major feedwater-technology combinations, capturing the vast majority of the total desalination capacity (>80%).

With increasing water demands coupled with water scarcity intensification, desalination is expected to expand rapidly in the future. The expected expansion in desalination capacity will be commensurate with an increase in the volume of brine produced. Management of the reject brine is the still a major problem of desalination (Roberts et al., 2010; Elimelech and Phillip, 2011; Mezher et al., 2011; Wenten, 2016), containing both elevated salinity (relative to feedwater type) and chemicals used during pre- and post-treatment phases in the desalination operation (Wenten et al., 2016). Traditionally, a variety of brine disposal methods have been used, including direct discharge into oceans, surface water or sewers, deep well injection and brine evaporation ponds (Morillo et al., 2014). The geographical location at which brine is produced influences the brine disposal method – desalination plants located near to large surface saline water bodies (ocean, seas) often discharge untreated waste brine directly into these water bodies (Arnal et al., 2005). Conversely, desalination plants located inland may not have a surface water discharge option available, and hence alternative brine disposal methods are required, of which there are few economically viable options (Arnal et al., 2005; Brady et al., 2005; Morillo et al., 2014).

Whilst the majority of brine is produced near to the coastline (Fig. 7a), with almost 80% of brine produced within 10 km (Table 5), a substantial volume of brine is produced in geographic locations where surface water discharge is likely not possible (Fig. 7b, Table 5). In addition, there are a variety of environmental concerns associated with the discharge of hypersaline brine into surface water bodies (Einav et al., 2002; Roberts et al., 2010; Palomar and Losada, 2011). Major concerns are related to the ecological effects associated with physio-chemical alterations (e.g. increased salinity) to seawater around brine discharge outlets and the discharge of toxic chemicals used in water pre-treatment or as anti-scalants and anti-foulants in the desalination process (Einav et al., 2002; Roberts et al., 2010; Ketsetzi et al., 2008). When continually discharged to surface waters, these factors pose risks to ocean life and marine ecosystems (Gacia et al., 2007; Palomar and Losada, 2011; Meneses et al., 2010). The high salinity of brine causes elevated density in comparison to the salinity of the receiving waters, which can form "brine underflows" that deplete dissolved oxygen (DO) in the receiving waters. High salinity and reduced DO levels can have profound impacts on benthic organisms, which can translate into ecological effects observable throughout the food chain (Rabinowitz, 2016; Frank et al., 2017). A combination of these factors necessitates the development of new brine management strategies that are both economically feasible and environmentally sound.

Recent efforts have focused on ways to treat or use brine in order to minimise or eliminate the negative environmental impacts associated with brine disposal (Morillo et al., 2014; Wenten et al., 2017) and/or to partially or fully offset the economic costs associated with brine disposal (Kesieme et al., 2013; Morillo et al., 2014). These efforts cover a range of techniques with variable levels of complexity and cost. For example, mixing brine with alternative water sources of a lower salinity (e.g. treated wastewater, power-plant cooling water) can reduce brine salinity by dilution (Giwa et al., 2017). Pressurised dispersion nozzles can promote mixing of brine waters with receiving waters, restricting bottom ponding (Roberts, 2015). Techniques such as bipolar membrane electrodialysis (BMED) can convert brine into acid and base products for reuse, such as NaOH and HCl (Ibáñez et al., 2013; Morillo et al., 2014). Metal recovery from brine offers a valuable source of many scarce metals (e.g. uranium), whilst potentially reducing environmental impacts associated with mining (Morillo et al., 2014; Loganathan et al., 2017). The high economic costs and energy demands of brine treatment and mineral recovery methods remain a significant barrier to more widespread application (Kaplan et al., 2017). Comprehensive reviews of the recent techniques, technologies and innovations in brine management are provided by Morillo et al. (2014) and Giwa et al. (2017).

Other potential economic opportunities associated with brine production have also sparked a wave in innovation in brine management that seeks to turn an environmental problem into an economic opportunity (Sánchez et al., 2015). For example, Blackwell et al. (2005) identified sequential biological concentration (SBC) of saline drainage streams creating a number of financial opportunities, whilst concentrating the waste stream into a manageable volume. Qadir et al. (2015) suggested that integrating agriculture and aquaculture systems based on the SBC system using saline drainage water sequentially has the potential for commercial, social and environmental gains. Reject brine has been used for aquaculture, with increases in fish biomass of 300% achieved (ICBA, 2018). Reject brine has also been successfully used for Spirulina cultivation and the irrigation of halophytic forage shrubs and crops although this method was unable to prevent progressive land salinisation (Sánchez et al., 2015).

Aside from treating or using reject brine, a method to reduce the volume of brine produced is to improve the water recovery ratio of desalination plants. Desalination plants operating with a high RR are favourable in that they both maximise the use of (often scarce) water resources as in the case of river and brackish water desalination plants and create a lower volume of concentrate for disposal (Harvey, 2008), reducing the economic costs associated with brine disposal. High recovery rates can also reduce the cost of pre-treatment prior to desalination and post-treatment of brine (Lachish, 2002). However, attaining higher RRs generally increases energy demands and hence treatment costs (Lachish, 2002), increasing greenhouse gas emissions if the desalination plant is powered by fossil fuels (Martin-Gorriz et al., 2014; Darre and Toor, 2018). Whilst the reduced volume of brine associated with higher RRs might have positive environmental implications, the brine salt concentration will be increased (Ahmed et al., 2001) which could potentially pose harmful risks to the aquatic environment following disposal (Bashitialshaaer et al., 2009). Determining the optimal recovery ratio for desalination plants is therefore an economic, environmental and technical challenge, requiring consideration on a site-by-site basis.

5. Conclusions & outlook

Against the backdrop of increasing global water scarcity, desalinated water is increasingly becoming a viable option to narrow the water demand-supply gap, particularly in addressing domestic and municipal needs. Desalinated water can substantially extend the volume of high-quality water supplies available for human use. A steady and assured supply of high-quality water is crucially important in an era when the world at large is embarking on the Sustainable Development Agenda to ensure access to safe water for all by 2030, and for the achievement of SDG 6 to safeguard water supplies for current and future generations. In addition to SDG 6, a variety of other SDGs are inextricably linked with water resources management, such as SDG 2 aiming at zero hunger, SDG 3 ensuring healthy lives, SDG 8 promoting sustainable economic growth, SDG 11 making cities and human settlements inclusive, and SDG 13 combating climate change. These SDGs have water-related targets that must be achieved before their ultimate realisation is possible.

Although desalination can provide an unlimited, climate-independent and steady supply of high-quality water, there are specific challenges to harness the vast potential of desalinated water, such as relatively high economic costs and a variety of environmental concerns. A major environmental concern arises from the large volume of brine produced in the desalination process that requires management. Brine management is both economically expensive and technically difficult, and hence most desalination plants discharge untreated brine directly into the environment. Addressing these challenges, research studies have demonstrated that there are economic opportunities associated with brine, such as commercial salt and metal recovery and use of brine in fish and halophyte production systems. There is a need to translate such research to convert an environmental problem into an economic opportunity. This is particularly important in countries producing large volumes of brine with relatively low efficiencies, such as Saudi Arabia, UAE, Kuwait and Qatar.

Although smaller amounts of desalinated water are used for the power and irrigation sectors, water is desalinated primarily for municipal and industrial purposes. In this regard, desalinated water provides a safe and sustainable source of good-quality water for domestic purposes. Such potable water supplies are critically important in water scarce areas where water quality deterioration is also on the increase. The use of desalinated water in producing high-value crops and crop commodities would be another avenue whilst considering expansion of desalinated water to other sectors (Silber et al., 2015).

Due primarily to the relatively high economic costs, desalination is currently concentrated in high income and developed countries. There is a need to make desalination technologies more affordable and extend them to low income and lower middle income countries, increasing the viability of desalination for addressing SDG 6 in areas that developments have previously been limited by high economic costs. To do this, technological refinement for low environmental impacts and economic costs, along with innovative financial mechanisms to support the sustainability of desalination schemes, will likely be required. The expansion pattern and economics of desalination facilities in recent decades suggest a positive and promising outlook for expansion in desalination facilities around the world.

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Conflicting interests

The authors declare no conflict of interest.

Appendix A. Supplementary information

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.12.076.

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