THE STATE OF DESALINATION AND BRINE PRODUCTION

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Contents

Summary

Access to clean water is vital for protecting life, livelihoods and for achieving sustainable development. Trends towards increasing water demands, decreasing clean water availability and urbanization are exacerbating water scarcity in most world regions. Conventional water resources such as lakes, rivers and aquifers fed by rainfall, snowmelt and river runoff are becoming increasingly overstressed, with trends in water conservation and improved water use efficiencies insufficient to close the supply-demand gap. Unconventional water resources, such as desalination and treated wastewater re-use, are increasingly recognized as viable options for water supply enhancement. Continually improving unconventional water resources technologies have permitted more efficient and economical tapping of water resources which were previously unusable due to access constraints or the added costs related to unsuitable water quality. Desalination can either extend clean water availability beyond what is available from the hydrological cycle (e.g. seawater) or improve the quality of existing water sources below sectoral thresholds (e.g. brackish water). Whilst desalination has enormous potential, specific barriers pose constraints to its widespread application. Barriers include economic costs, greenhouse gases emissions and effluent management. The disposal of a concentrated effluent stream (brine) produced in the desalination process simultaneously poses technical, economic and environmental challenges.

Elevated levels of salinity and temperature, in addition to the presence of chemicals used in the desalination process, pose risks to ecosystems in the vicinity of the plant outlet. The development, regulation and enforcement of environmentally friendly brine disposal methods are imperative for mitigating these risks. Furthermore, a growing body of research indicates a variety of economic opportunities associated with brine management. Development and commercial implementation of these technologies provides exciting opportunities for lowering both the economic costs and environmental risks of desalination and hence should be a priority for future research.

1. Introduction

Clean water is essential for supporting human livelihoods and achieving sustainable development, and crucial for maintaining ecosystem health. Most major human activities, such as crop and livestock production, manufacturing of goods, power generation and domestic activities rely upon the availability of water in both adequate quantities and of acceptable quality at the point of intended use (van Vliet et al., 2017).

Shortage of water supplies in both adequate quantities and qualities for various human activities is already recognised as a major global threat, with 'water crisis' frequently classified as one of the top risks to humankind in terms of both likelihood and severity of potential impacts. Failure to address these challenges not only threatens the achievement of Sustainable Development Goal 6 (SDG 6) to safeguard water supplies for current and future generations, but is also inextricably prohibitive for achieving zero hunger (SDG 2), ensuring healthy lives (SDG 3), promoting sustainable economic growth (SDG 8) and combating climate change (SDG 13).

Whilst freshwater availability exceeds demand at the global level, geographical and temporal mismatches between availability and demand induce conditions of water scarcity in certain regions and at certain times. Water scarcity can be defined as "the condition wherein demand for water by all sectors, including the environment, cannot be satisfied fully due to the impact of water use on supply or quality of water" (Liu et al., 2017). Water scarcity has typically been quantified as the ratio of water withdrawal to the overall water availability (termed the 'criticality ratio'). Notably, this approach has been adopted by the United Nations (UN) as the principal indicator of water scarcity through Sustainable Development Goal (SDG) 6.4.2.

Human water demands are increasing as a result of a rising human population, increased water consumption per capita and economic growth, whilst simultaneously the availability and quality of conventional water resources are being affected by climate change, unsustainable water extractions and anthropogenic contamination. The mismatch between the demand for, and supply of, good quality water has exacerbated water scarcity in most world regions (Wada et al., 2016). These trends are projected to extend and intensify into the future, exacerbating competition for (scarce) water resources, increasing the frequency, duration and intensity of extreme hydro-meteorological disasters (e.g. droughts) and thereby increasing the number of people experiencing conditions of severe water scarcity.

Conventional renewable water resources, such as lakes, rivers and aquifers fed by rainfall, snowmelt and river runoff, have become increasingly scarce and overburdened. Supply side management approaches such as water conservation and improved water use efficiencies, particularly in the irrigated agricultural sector, play an important role in alleviating water scarcity. However, these improvements are not conducive to efficient water management, as the supply-demand gap would only close by 20% by 2030 (World Bank, 2019). As such, these strategies must be combined with supply enhancement. Conventional water supply enhancement strategies, including river regulation, reservoir construction and water transfers, ultimately still rely on the natural hydrological cycle. Furthermore, these strategies can face strong social opposition and conflict; such as forced relocation of people, altered downstream flow regimes and habitat degradation or alteration (e.g. blockage of fish migration paths). A growing set of viable yet unconventional water resources are expected to play a key role in the provision of clean water for sectoral uses, improving ecosystem health, supporting climate change adaptation and for achieving sustainable development (Jones et al., 2019).

Unconventional water resources encapsulate a range of strategies across different geographic scales, from localized fog-water and rainwater harvesting, to mega-scale desalination plants and wastewater treatment and re-use facilities. The use of unconventional water resources for clean water provision has been rapid, often arising out of the lack of viable conventional alternatives and to increase diversification of water sources. This trend is expected to continue and accelerate into the future, with continual technological improvements permitting access to water sources which were previously unusable due to access or economic constraints (Ghaffour et al., 2013). The increasing unreliability, economic cost and accessibility to water from conventional sources will also drive this trend. Furthermore, increasing industrial water requirements, mandatory restrictions and enforced regulations on freshwater abstraction ~~extraction~~ and consumption from conventional sources, combined with elevated public awareness and recognition of water-related issues will promote both the acceptance for and use of unconventional water resources.

Desalination is a well established technology applicable to unconventional water resources. In essence, desalination is the process of removing salts from water to a level which meets the quality (salinity) requirements for a particular human purpose (sectoral user). Desalination has primarily been applied to meet water demands of the domestic and industrial sectors, particularly in high-income arid countries (e.g. Saudi Arabia, UAE, Kuwait) and small island nations (e.g. Malta, Cyprus) which lack sufficient access to conventional water resources. However, with rising costs and diminishing supplies and security of conventional water resources, coupled with technological advances and decreasing energy and economic costs, desalination is increasingly becoming an attractive water resources management around the globe. Whilst the benefits and potential of desalination are irrefutable, specific challenges primarily related to economic and environmental costs remain. Of these challenges, economic costs, greenhouse gas (GHG) emissions and the safe disposal of effluent (henceforth ‘brine’) entailed in the desalination process pose significant technical, environmental and economic challenges. Overcoming these challenges is essential for ensuring the compatibility of desalination with the Sustainable Development Agenda and for promoting the safe implementation of these technologies to combat water scarcity.

Section 2 provides an introduction to desalination, highlighting the past trends and potential future drivers of the technologies. Section 3 gives an overview of the current global state of desalination, while Section 4 highlights the considerations, challenges and opportunities associated with desalination. A major challenge highlighted in this Chapter is the production of brine. Section 5 provides an overview of the current global state of brine production from desalination. Section 6 further explores the specific challenges posed by brine disposal, whilst also highlighting various economic opportunities associated with alternative brine management practices.

2. Desalination: Past Trends and Future Drivers

Desalination is fundamentally a water treatment process aimed at removing dissolved salts from water sources that, prior to treatment, are too salty for an intended use. Typically, the feedwater is sourced from seawater, or from brackish surface or groundwater sources. The major users of desalinated water have been the domestic and industrial sectors due to their requirements for high quality water. Desalination has long been recognized as a technique for producing fresh water from saltwater, although significant investment and research into desalination emerged in the 1940s. Two major categories of desalination currently exist: thermal processes and membrane processes. Thermal processes involve a phase change - saline water is heated to create water vapor, which condenses to pure water and separates from its salt and impurities in the process. Conversely, in membrane processes, saline water is forced through a membrane which selectively allows water molecules to pass whilst retaining salts.

While many different desalination technologies exist, with more technologies in the research and development phase, the market remains dominated by two thermal technologies: multi-stage flash (MSF) and multi-effect distillation (MED); moreover, the market is dominated by one membrane technology: reverse osmosis (RO) (Figure 1). In MSF, feedwater passes through a series of tanks (termed 'stages') at progressively lower pressures. At each stage, part of the feedwater boils ('flashes') and forms vapor which condenses to freshwater on heat-exchange tubes. Freshwater is collected, whilst the remaining (more saline) feedwater passes through to the next stage (at lower pressure, to lower the boiling point) where a portion will again flash and condense to freshwater, and so on, for between 4 – 40 stages. Similarly, MED occurs in a series of stages (termed 'effects') and follows a similar principle of condensation and evaporation under sequentially reduced ambient pressure at the various effects. However, in MED, vapor formed in each effect flows into the next chamber and condenses, releasing heat that acts as a thermal energy source for heating that effect. Usually, 8-16 effects are used in large MED desalination plants. In RO, feedwater is forced (under pressure) through a semi-permeable membrane which selectively enables water to pass whilst retaining ions, molecules and large particles. Unlike MED and MSF, feedwater undergoing RO must receive extensive pre-treatment to avoid membrane fouling. Typical pre-treatment steps can be chlorination for biological fouling (e.g. bacteria, micro-organisms) and filtration for particle fouling (e.g. sand, clay). Most other commercial desalination technologies use membranes, such as nanofiltration (NF), electrodialysis (ED) and electrodialysis reversal (EDR). Whilst these technologies have been rapidly developing in recent years, their relative market shares remain low with respect to the more established desalination technologies.

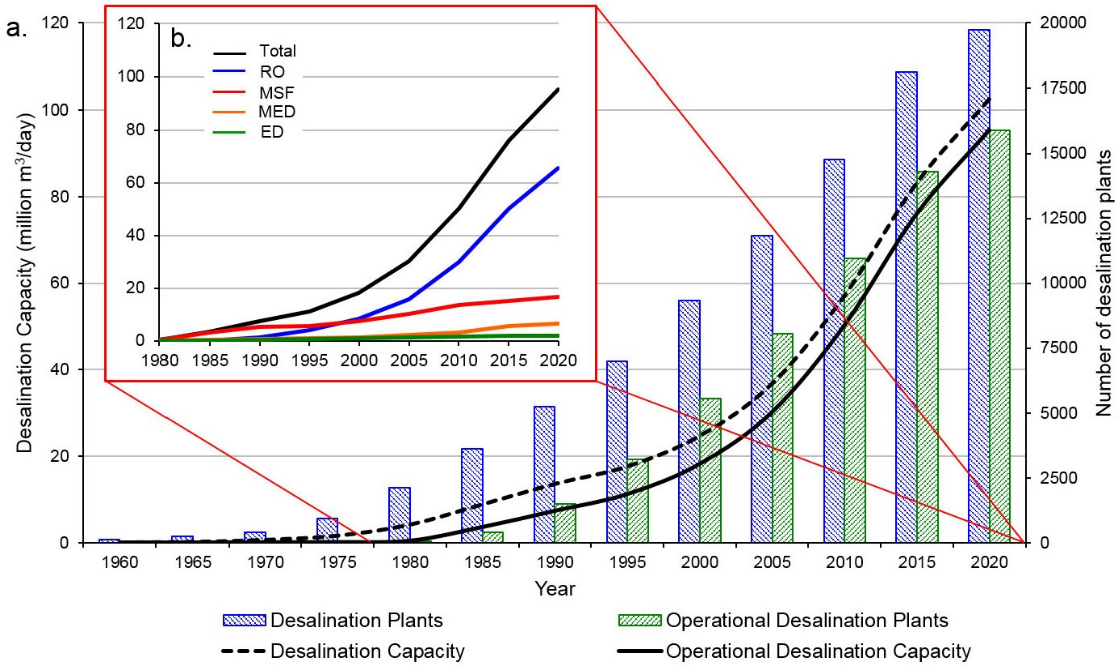

Figure 1. Trends in global desalination by (a) number and capacity of total and operational desalination plants, and (b) operational capacity by desalination (Jones et al., 2019)

The earliest commercial desalination plants were predominantly located in oil-rich but water scarce regions, most notably in the Middle East from the 1960s onwards. These desalination plants primarily utilized thermal desalination technologies (MSF, MED), facilitated by the abundant quantities of affordable energy, to produce water both for municipal and industrial applications. The overwhelming dominance of thermal desalination technologies endured until 1970, where MED and MSF accounted for 95% of the global desalinated water production. From the early 1970s onwards, desalination using membrane processes, particularly reverse osmosis, began to increase rapidly both in the number of plants and in treatment capacity. Throughout the 1970s and 1980s, the market share of desalination via membrane processes increased from less than 5% in 1970, to 16% in 1975, to 28% by 1980. By 2000, desalinated water production from reverse osmosis (11.4 Mm^3/day) was approximately equal to that of thermal processes (11.6 Mm^3/day). Since the turn of the century, the market share of membrane technologies has grown relatively consistently at between 5-7% per year. This growth has continued until present day, whereby membrane processes account for ~73% of desalinated water production. The trends in global desalination by the number and treatment capacity of desalination plants, disaggregated by technology type, are displayed in Figure 1. A comprehensive overview of the current global state of desalination is provided in Section 3.

The use of desalination as an unconventional water resource is expected to continue and extend, driven by a mixture of hydrological, technological, economic and social factors. The key driver of desalination is water scarcity. Rising water demands due to population growth and economic growth, coupled with diminishing water supplies due to climate change and contamination, are exacerbating water scarcity in most world regions (Wada et al., 2016). With the mismatch between water supply and demand, across different spatial and temporal scales, expected to continue and grow in the future, desalination will become an increasingly attractive supply enhancement option. Favorable economic aspects may also promote and stimulate future use of desalination. The price per m^3 of desalinated water has generally been falling steadily, although site conditions such as the desalination technology, feedwater type, energy source and size of desalination plants are important factors influencing the cost of desalinated water. Continued improvements in desalination technologies, such as membranes and energy recovery devices, offer opportunities for further reducing the overall economic cost of desalinated water production. Furthermore, the rising cost of water from conventional sources will likely increase the cost competitiveness of freshwater produced from desalination.

Legislation and regulatory policy may either act as a driver or deterrent of desalination in the future. The development and enforcement of stricter regulations regarding freshwater extraction and consumption from conventional water resources, particularly groundwater, could encourage or even necessitate alternative supply options. Where geographically and economically applicable, this shortfall could be met through increased desalination. This will likely influence particularly industrial uses, which are often considered of lower priority for allocation than the domestic sector. Desalination for industrial purposes will likely also increase independent of regulation as a response to increasingly unreliable water supplies in terms of quantity and quality, especially for applications which require extremely high quality (low salinity) water such as the pharmaceutical industry. However, trends towards stricter environmental guidelines and regulations may negatively influence or slow the use of desalination. In terms of social barriers to desalination, these are typically much lower than other water supply schemes such as dam building and water transfers, or to other unconventional water resources such as the re-use of treated wastewater particularly as potable water. Overall, with increased public awareness of the global water challenge, there is increased recognition of the importance of both water conservation and diversification of water resources, which may promote the further use of desalination. For a more comprehensive overview of the considerations, challenges and opportunities associated with desalination, refer to Section 4.

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Bibliography

Elimelech, M., and Phillip, W. A. (2011) The Future of Seawater Desalination: Energy, Technology, and the Environment, *Science*, 333, 712, https://doi.org/10.1126/science.1200488. [Review of the future changes in energy consumption, developments in technologies and the sustainability of desalination as a solution to water scarcity]

Eltawil, M. A., Zhengming, Z., and Yuan, L. (2009*)* A review of renewable energy technologies integrated with desalination systems, *Renewable and Sustainable Energy Reviews,* 13, 2245-2262, https://doi.org/10.1016/j.rser.2009.06.011. [Overview of the production of desalination with renewable technologies, with emphasis on technologies and economics]

Ghaffour, N., Missimer, T., and Amy, G. (2013) Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability, *Desalination*, 309, 197–207, https://doi.org/10.1016/j.desal.2012.10.015. [Current and future of desalination economics]

Liu, J., Yang, H., Gosling, S., Kummu, M., Flörke, M., Pfister, S., Hanasaki, N., Wada, Y., Zhang, X., Zheng, C., Alcamo, J., and Oki, T.: Water scarcity assessments in the past, present and future, Earth's Future, 5, https://doi.org/10.1002/2016EF000518, 2017. [Overview of water scarcity assessments]

Jones, E., Qadir, M., van Vliet, M. T. H., Smakhtin, V., and Kang, S.-m. (2019) *The state of desalination and brine production: A global outlook*, Science of The Total Environment, 657, 1343-1356, https://doi.org/10.1016/j.scitotenv.2018.12.076. [Comprehensive overview of the global state of desalination and brine production]

Mezher, T., Fath, H., Abbas, Z., and Khaled, A. (2011) Techno-economic assessment and environmental impacts of desalination technologies, *Desalination*, 266, 263-273, https://doi.org/10.1016/j.desal.2010.08.035. [Review of desalination technologies and their economic costs, environmental impacts and potential for technology improvements].

Morillo, J., Usero, J., Rosado, D., El Bakouri, H., Riaza, A., and Bernaola, F.-J. (2014*)* Comparative study of brine management technologies for desalination plants, *Desalination*, 336, 32-49, https://doi.org/10.1016/j.desal.2013.12.038. [Overview of brine management technologies and an analysis of the technologies advantages, drawbacks, feasibility and development stage]

Petersen, K., Heck, N., Reguero, B. G., Potts, D., and Hovagimian, A. (2019) Biological and Physical Effects of Brine Discharge from the Carlsbad Desalination Plant and Implications for Future Desalination Plant Constructions, *Water*, 11, 208, https://doi.org/10.3390/w11020208. [A recent case study for the biological and physical effects of brine discharge and recommendations for appropriate brine disposal options]

Roberts, D. A., Johnston, E. L., and Knott, N. A. (2010) Impacts of desalination plant discharges on the marine environment: A critical review of published studies, *Water Research,* 44, 5117-5128, https://doi.org/10.1016/j.watres.2010.04.036. [Review article highlighting the potential impacts of brine on ecosystem health]

UN-Water (2020) *UN-Water Analytical Brief on Unconventional Water Resources*. Geneva, Switzerland. [Comprehensive analytical brief highlights the wide range of unconventional water resources, including desalination. Also analyses the interlinkages with the Sustainable Development Agenda and addresses non-technical aspects of unconventional water resources]

van Vliet, M., Flörke, M., and Wada, Y. (2017) Quality matters for water scarcity, *Nature Geoscience*, 800-802, https://doi.org/10.1038/ngeo3047, 2017. [Overview of water quality considerations for water scarcity assessments]

Wada, Y., Flörke, M., Hanasaki, N., Eisner, S., Fischer, G., Tramberend, S., Satoh, Y., van Vliet, M. T. H., Yillia, P., Ringler, C., Burek, P., and Wiberg, D. (2016) Modeling global water use for the 21st century: the Water Futures and Solutions (WFaS) initiative and its approaches, *Geosci. Model Dev.*, 9, 175-222, https://doi.org/10.5194/gmd-9-175-2016. [Detailed analysis of future water demands and linkages to water scarcity]

World Bank (2019) *The Role of Desalination in an Increasingly Water-Scarce World*. World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/31416 License:

CC BY 3.0 IGO, 2019. [Very comprehensive of overview of desalination as a water supply enhancement strategy, including detailed explanation of the different technologies and the likely future developments in the sector. Very extensive overview of the economics of desalination and considerations for its implementation]

Biographical Sketches

Edward Jones is a PhD candidate at Utrecht University under the supervision of Dr. Michelle T.H. van Vliet and Prof. Dr. Ir. Marc Bierkens. His PhD project, entitled ‘Water scarcity under global change: accounting for water quality and unconventional water resources’, aims to further current efforts to conduct water quality modeling at the global scale and to investigate the role of water quality in quantifications of current and future water scarcity. Inherently connected to both water quality and scarcity, this project also seeks to incorporate the fast growing yet unconventional water resources into the water quality and water scarcity frameworks. In particular, wastewater treatment is a key influencer of water quality, whilst supply enhancement options such as wastewater re-use and desalination can be utilized to reduce water scarcity from both a quantity and quality perspective. Whilst such options provide exciting progress towards many interconnected SDGs such as the achievement of a water secure future for all, the potential environmental negatives of these technologies must be considered and mitigated.

Manzoor Qadir is an environmental scientist with a focus on water-related sustainable development through contribution to policy, institutional and biophysical aspects of unconventional water resources, water recycling and safe reuse, water quality and environmental health, and water and food security under changing climate. Manzoor has implemented multidisciplinary projects and directed research teams in different regions of the world. He has undertaken several international capacity development initiatives such as organizing knowledge bridging workshops and training courses. Before joining UNU-INWEH in Canada, Manzoor previously held professional positions at ICARDA and IWMI; Visiting Professor at Justus-Liebig University, Germany; and Associate Professor at the University of Agriculture, Pakistan. He is a fellow of the Alexander von Humboldt Foundation, Germany, and brings his expertise to many scientific and advisory committees.