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Desalination in the 21st Century: A Critical Review of Trends and Debates

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ABSTRACT: Desalination – or the creation of 'new' water by removing salt and impurities from saline, brackish or contaminated water – has transformed water resource management in many parts of the world. This technology is likely to continue to reshape the practices, politics and political economy of water throughout the 21st century. Desalination has long been a focus of research in techno-managerial and techno-triumphalist circles, but as global capacity has grown and as new water infrastructures have developed in more diverse and contested contexts, it has increasingly attracted debate in the critical social sciences and humanities. This paper offers a critical review of the current state of the desalination debate. The paper proceeds in three parts. First, it sketches out the contours of desalination's uneven global emergence as a game changer in water resource management, briefly introducing the reader to its technical aspects and highlighting key trends. Second, the paper examines differing interpretations of the *drivers* of this phenomenon. The paper challenges dominant and reductionist explanations that tend to highlight water scarcity as an external factor, population growth and industrialisation. Instead, it foregrounds four alternative explanations for the extraordinary growth of desalination as: 1) a tool for fixing insoluble political issues in water management; 2) a technological adaptation that reflects and reinforces processes of decentralisation in water management; 3) a source of reliable long-term revenue for increasingly financialised models of water service provision; and 4) a driver of growth in particular industries and economic sectors. Finally, the paper suggests some future directions for critical desalination research.

KEYWORDS: Desalination, political ecology, water security, hydropolitics, transitions

> *Unconventional times call for unconventional water resources.*
>
> UN-Water, 2020.

> *The distinctive features of capitalism as a mode of production continuously seek to transcend the land – sea binary in an incessant quest for profit, thereby engendering new articulations of terraqueous territoriality – that is, uniquely capitalist alignments of sovereignty, exploitation and appropriation in the capture and coding of maritime spaces and resources.*
>
> Campling and Colás, 2021: 3.

INTRODUCTION

Desalination – or the removal of salt and impurities from saline, brackish or contaminated water to create freshwater – has transformed water resource management in many parts of the world, and is likely to continue to reshape the practices, politics and political economy of water throughout the 21st century. Indeed, it is difficult to overstate the significance of the desalination phenomenon. Total global capacity for the production of fresh water via desalination has increased from around 5 million cubic metres per day (m^3/day) in 1980, to 20 million m^3/day in 2000, to around 90 million m^3/day in 2020, with all major market forecasters predicting that this trend will continue in coming decades (IDA, 2020). Desalination is now a major source of fresh water for municipal and private supply in diverse contexts; it also fulfils a host of industrial and other economic functions including the production of extremely pure water for manufacturing and the cleaning of industrial effluents. Although often overlooked, the production of new water resources via desalination has quietly become central to the metabolic circulation (Swyngedouw, 2006) of cities, regions and even countries around the world. This paper argues that desalination should be understood as a resource frontier in two regards. First, it allows societies to tap into new water resources in the face of dwindling or contested traditional supplies, with the huge cost of desalination signalling the end of 'cheap water' in certain places (O'Neill, 2020). Second, desalination has become a frontier of accumulation – or a new gold rush – increasingly the focus of investment because of its capacity (under the right conditions) for generating stable long-term revenue (Loftus and March, 2016; Pryke and Allen, 2019). The emergence of desalination therefore reflects and reinforces the realignment of society – water relations along uniquely capitalist lines.

This review, as the title suggests, focuses on the debates surrounding desalination as contested terrain. The literature on desalination is currently focused overwhelmingly on its technical and managerial aspects. For example, there is an entire Elsevier journal dedicated to the science and technology of water purification by desalination (with an impact factor over 7), which was launched in 1966 (see Ashraf et al., 2022). Much of this work is either techno-triumphalist – highlighting the virtues of desalination for society (reliable water supply, climate change adaptive, and so forth – or is narrowly concerned with mitigating the negative aspects of this technology. There is also a very large body of literature that explores the environmental impacts of the desalination process across its various phases (for reviews, see Lee and Jepson, 2021; Lior, 2017; Wilder et al., 2016). Particular attention has been paid to the high energy intensity of membrane and thermal desalination and the concomitant stresses this places on energy systems and energy-related greenhouse gas emissions (Yoon et al., 2018). Other environmental impacts include the loss of marine life through intakes, the use of toxic chemicals in membrane cleaning and anti-fouling, and the disposal of highly saline brine discharge; the latter is of particular concern for inland brackish water desalination where brine cannot be discharged directly into the sea (Jones et al., 2019). More critical work has dealt with the sociopolitical implications of the water-energy interconnections that are being driven by desalination (McDonnell, 2014) and by the implications these interconnections have for climate change (Tubi and Williams, 2021).

This paper engages with the debates around desalination from a hydrosocial perspective (Boelens et al., 2016; Linton and Budds, 2014) and builds on several previous reviews of desalination from critical geography and the social sciences (March, 2015; Morote et al., 2017; Williams and Swyngedouw, 2018). These reviews have made important arguments about the political, economic and social dimensions of desalination and the ways in which desalination is contested. The paper updates this fast-moving and dynamic debate, and it builds on these contributions by setting out a series of explanations for what is driving desalination and by highlighting future directions for research. The paper has three main aims. First, it sketches out the contours of desalination's emergence as a game changer in water resource management in the 21st century, offering a brief introduction to its technical aspects and highlighting key trends. Second, it explores the various explanations for this phenomenon. It rejects the overly reductionist interpretations propagated by the techno-managerial literature that revolve around deterministic frameworks of population growth, climate change, supply/demand relationships, and technological development – a perspective that is encapsulated by the UN-Water report quoted above. The paper, instead, highlights four alternative explanations found in the literature for the uneven globalisation of desalination in the 21st century, namely that it is being driven by: technopolitical factors;

ongoing processes of decentralisation in water management and the changing character of the modern hydraulic state; the growing function of infrastructure as a source of revenue for financial actors entering the field of water management; and pressure to facilitate economic growth in particular economic sectors. Finally, the paper explores some of the gaps in the desalination debate so far and suggests three potential avenues for future research.

A 21ST CENTURY PHENOMENON

The global emergence of desalination as a significant component of water supply should be understood, first and foremost, as a phenomenon peculiar to the 21st century. Certainly, simple techniques of removing salt from water have existed for thousands of years (Birkett, 2010) and there is also an interesting history of desalination in the 20th century, with the first municipal plants emerging as early as 1912 (El-Dessouky and Ettouney, 2002). The process was industrialised and commercialised during the second half of the 20th century, largely because of state-led research and development. In the United States, this occurred most notably following the 1952 Saline Water Conversion Act, and the establishment of the Office of Saline Water, which operated under the Department of the Interior until 1974. During this time, desalination was closely linked to the popular aspirations of the nuclear age and was anticipated to be a contributing technology to an imminent era of cheap energy and abundant water (Saurí et al., 2018). There were several attempts to twin the production of energy via nuclear technology with the production of water via desalination, although by the 1970s it was clear that 'nuclear desalination' would not become the panacea many had hoped. Desalination, instead, became deeply connected to fossil fuel energy regimes, particularly in the Arabian Gulf where abundant oil and gas resources have powered desalination plants (often through combined energy/water production infrastructures) and where state oil revenues have long been used to subsidise water services (Barau and Al Hosani, 2015; Low, 2020). Since the middle of 20th the century, then, the production of water via desalination has been inseparably linked with dominant energy regimes, first with nuclear imaginaries, then with fossil fuels, and now with ambitions of 'sustainable' and 'green' water supply that is powered by renewable energy (Bundschuh et al., 2021).

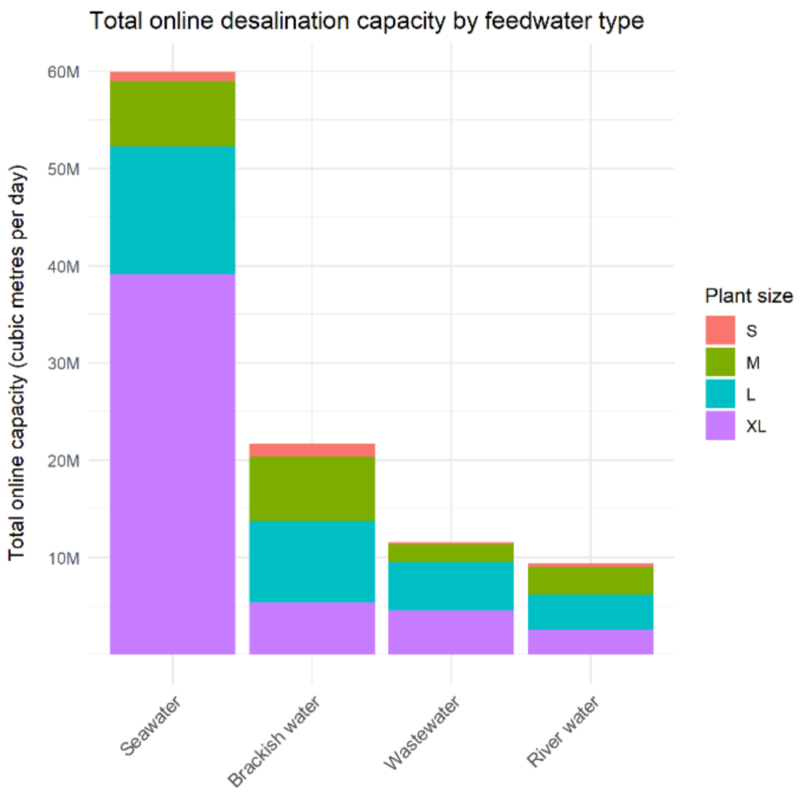
During the 1960s, desalination also briefly became an important geopolitical focus. In the context of the Cold War, desalination was one of the few areas of cooperation and technology-sharing between the United States and the Soviet Union because of its anticipated potential to transform the world's fresh water resources (Low, 2020). In 1967, the potential of desalination to solve water problems featured prominently in the discussion at the International Conference on Water for Peace. At the time, this event was one of the largest meetings ever held in Washington, DC, with delegates from 94 countries and more than 600 technical papers delivered. Its goal was to increase international efforts in the "furtherance of a worldwide cooperative effort aimed at the solution of water problems" (International Conference on Water for Peace, 1968: Vol 1, iii). As stated by one of the delegates in their opening remarks on the theme of Water Supply Technology,

> Few technical developments in history have attracted the attention and raised the hopes of so many as the promise of desalting the sea and brackish water. Civilization had its beginning where water was to be found, and its further development has ever been limited in nature's generosity – or lack of it – in providing water (…). While it may appear to be a self-evident point, I believe we cannot recall too often the fact that desalting alone, of the various proven means for dealing with water supply problems, actually increases the total supply of fresh water (Ramey, 1968, i).

Yet, with the exception of energy-rich states on the Arabian Peninsula, actual installed desalination capacity remained relatively modest throughout the second half of the 20th century and it was not until the late 1990s and early 2000s that desalination really took off (Figures 3 and 4). Several characteristics of the globalisation of desalination are worth noting.

1) *Desalination is about opening up new resource frontiers.* Desalination, as highlighted in the quotation above from the 1967 conference, is one of the few ways in which societies can create 'new' water resources that are independent of traditional terrestrial sources. Desalination fulfilled important functions during the 20th century, but it met only specific water demands in particular places (often for industrial purposes). The first two decades of the 21st century, however, have seen a widespread and large-scale appropriation of nontraditional water resources into the hydrosocial cycle. Desalination is an umbrella term for the removal of salt and impurities from a variety of nontraditional water sources. The oceans are the main new resource frontier, accounting for about 60% of global online desalination capacity; this is followed by brackish water resources, that is, primarily groundwater that was previously deemed too saline for use (about 22%). Wastewater, accounting for about 12% of capacity, is perhaps the next big water resource frontier after the sea, while low-concentration saline water, usually from river estuaries, accounts for about 9% (Figure 1). We should therefore understand desalination as a mechanism for the opening up, and exploitation, of a new resource frontier.

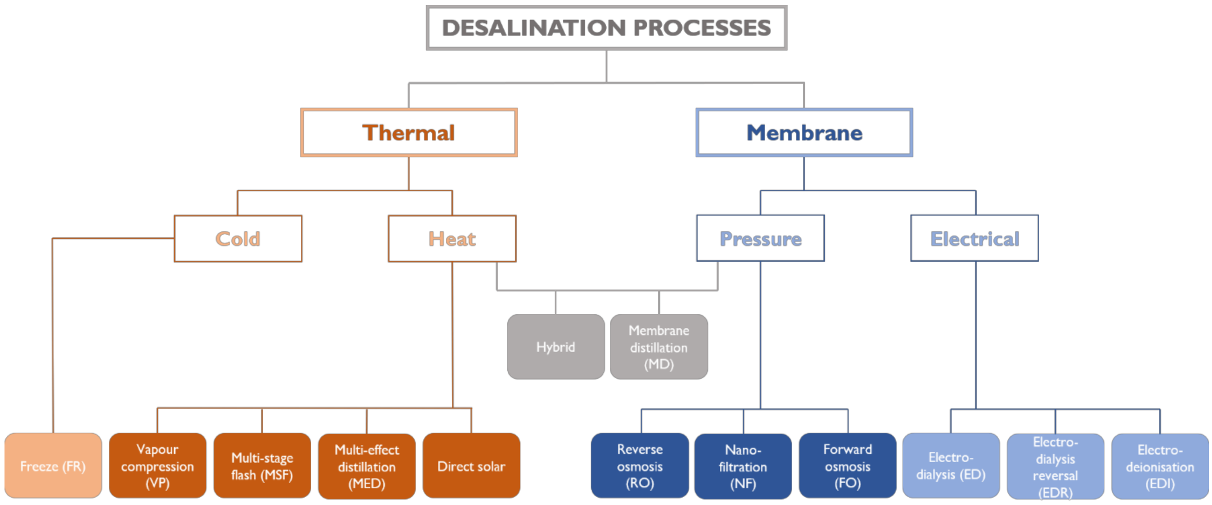
Figure 1. Global online and presumed-online desalination capacity by the four main resource frontiers, categorised by plant size.



Source: GWI DesalData (2021).

Note: S = under 1000 m3/day; M = 1000 to 10,000 m3/day; L = 10,000 to 100,000 m3/day; XL = over 100,000 m3/day. Source: GWI DesalData (2021).

Figure 2. Principal methods for desalinating water; reverse osmosis dominates in terms of installed capacity, followed by multi-stage flash and multi-effect distillation.



Note: For further information see Elimelech and Phillip (2011), Fritzmann et al. (2007), Pankratz (2004), Qasim et al. (2019), and Youssef et al. (2014).

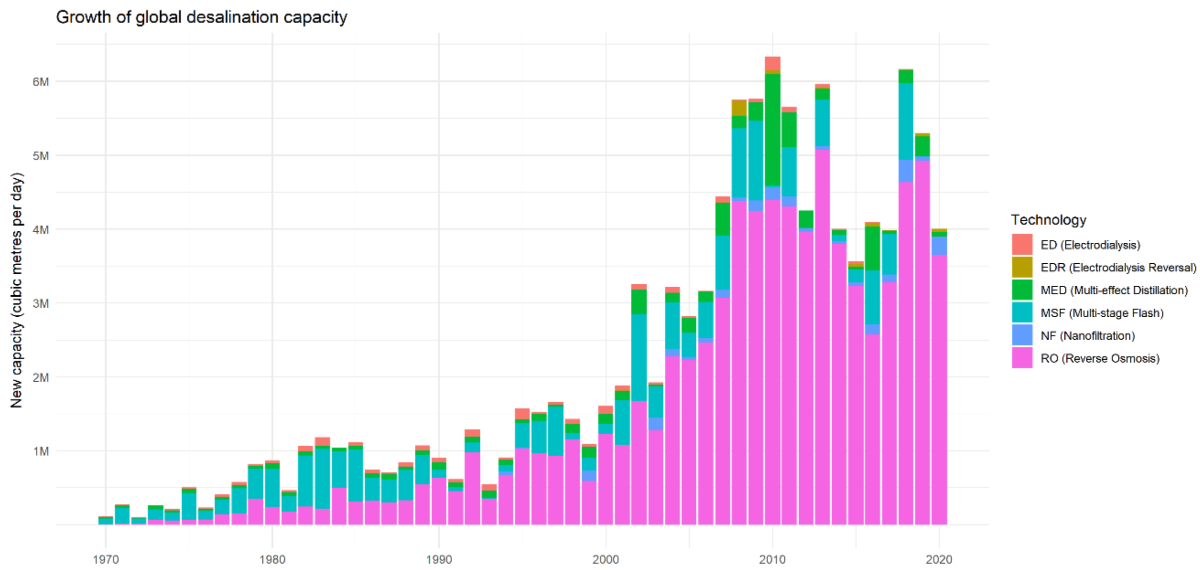
2) *Desalination is driving a particularly urban transformation.* Although agriculture accounts for around 70% of fresh water consumption globally, the use of desalinated water for irrigation is very limited because of its high cost. A small number of locations, such as in Israel, Morocco and Southeast Spain, have efficient irrigation systems where desalination is used for agriculture. Even in such places, desalinated water is used only for crops with high economic yield where prices justify the application of such expensive water (see Bernabé-Crespo et al., 2019; Martínez-Alvarez et al., 2017; Ricart et al., 2021). The Chtouka-Ait Baha desalination plant in the Souss-Massa region of Southern Morocco, for example, which was completed in 2022, supplies desalinated seawater for both domestic consumption and for the irrigation of 6070 hectares of agricultural land, producing mostly high-value greenhouse crops (Hirich et al., 2017; Magoum, 2022). It is the first large-scale seawater plant constructed to directly supply irrigation water. Beyond these few examples, however, it seems unlikely that desalination will form any significant part of agricultural water resource management in the near future. Indeed, one of the contradictions of desalination is that cities are increasingly turning to this resource, even in regions that maintain wasteful irrigation practices. As such, almost all growth in desalination has been driven by the municipal and industrial sectors and is therefore inextricably linked to processes of urbanisation (Morote et al., 2017). Furthermore, the desalination process allows for the production of water regardless of climate and geology, thus causing a disconnect, or rift, between the water regimes of urban landscapes and their physical environmental contexts (McDonnell, 2014).

3) *It is mainly about large-scale reverse osmosis (RO)*. There are many techniques for separating salt and water. All of the methods shown in Figure 2 are currently in use on an industrial or commercial scale and their suitability depends on a variety of factors including location, intended use of the water, energy supply, feedwater type, plant size, water quality requirements, and brine disposal options. Until the 1990s, the desalting industry was dominated by thermal processes, mainly multi-effect distillation (MED) and multi-stage flash (MSF) distillation; both of these use heat to evaporate/condense water. Since 2000, however, the vast majority of new capacity has utilised RO technology which involves forcing water through semipermeable membranes at high-pressure, usually in a cylindrical spiral-wound configuration. (The trend of increasing RO use is shown clearly in Figure

3.) The growth of RO was facilitated by a series of technological innovations in various aspects of the treatment process, most notably the development of energy recovery devices which have reduced the energy requirements of RO by about half; this new technology caused the process to become more cost-effective and reliable than thermal techniques (Stover, 2007). Various emerging technologies such as forward osmosis and solar desalination are attracting a great deal of attention, but there is no indication from industry forecasts that any of them will come close to challenging RO as the industry standard in the coming years (IDA, 2020). The global proliferation of desalination is therefore being driven primarily via the rollout of RO technology.

The global growth of desalting capacity is due almost entirely to the emergence of large and extra-large facilities,[1] Feitelson and Jones (2014) describe this as a "global diffusion" of large-scale desalination. Although small plants are far greater in number,[2] around 80% of the global capacity that is currently online or presumed online comes from large or extra-large facilities. (The trend towards the emergence of large-scale desalination is shown in Figure 4.) This is an important point because it illustrates the transformative character of contemporary desalination, in that large and extra-large facilities provide significant proportions of the total water supply in the cities and regions where they are located and often have supply capacities that are comparable to large dams.

Figure 3. New desalination capacity added each year globally (1970-2020), by technology type.

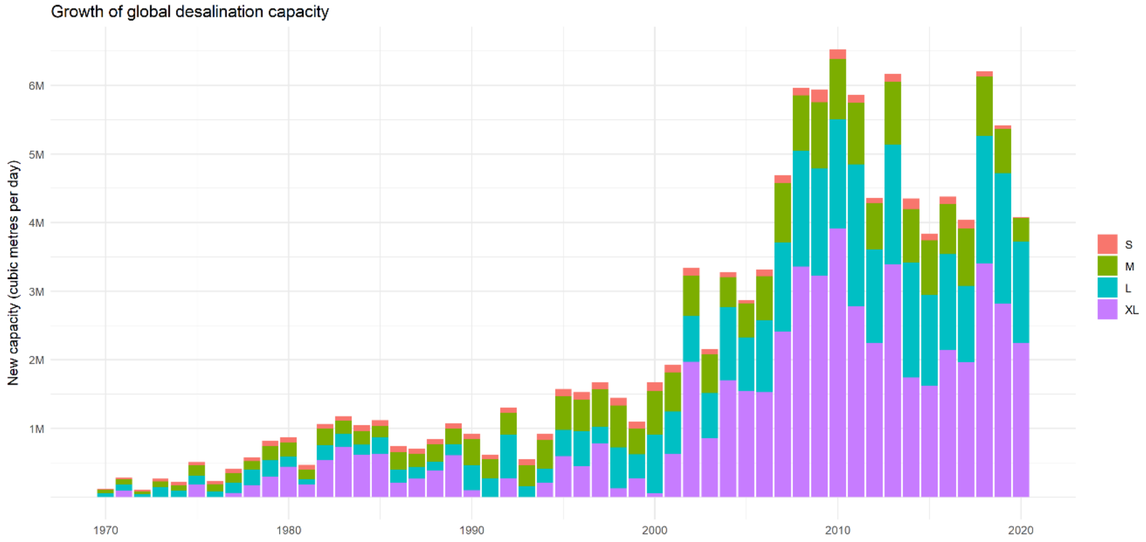


Source: GWI DesalData (2021).

[1] Global Water Intelligence's definition is used here, whereby 'large' refers to plants with capacities above 10,000 m^3/day and 'extra-large' refers to plants with capacities above 100,000 m^3/day.

[2] Of the 21,763 desalination plants monitored by GWI, 11,992 are classified as small, 7482 as medium, 1771 as large, and 446 as extra-large.

Figure 4. Desalination capacity added each year globally (1970-2020), by plant size.



Source: GWI DesalData (2021).

Note: S = under 1000 m^3/day; M = 1000 to 10,000 m^3/day; L = 10,000 to 100,000 m^3/day; XL = over 100,000 m^3/day.

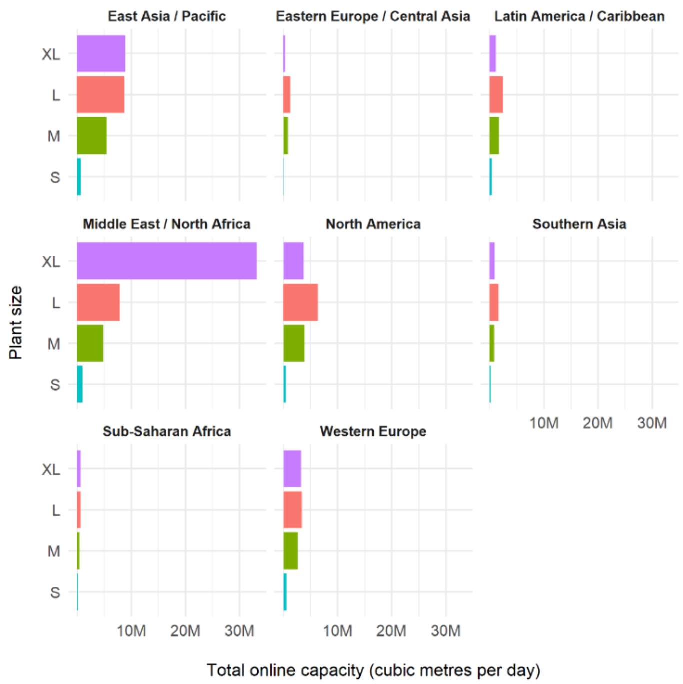
4) *As desalination has grown, so have its impacts.* Desalination represents a departure in some respects from the tensions and socio-environmental impacts of traditional (terrestrial) water infrastructure. Yet, these new metabolic processes embody substantial – and often structural – new contradictions (March, 2015; Swyngedouw and Williams, 2016). On the environmental side, the major impacts of desalination technology can be divided into those relating to water intake and waste output, and those relating to energy supply. In the 1990s and early 2000s, much of the concern about desalination focused on the impacts of highly saline brine discharge on marine environments (in the case of coastal/seawater desalination) and terrestrial environments (in the case of inland brackish desalination). These impacts tend to be localised and are highly context specific; for example, they tend to be more severe for older desalination plants where little consideration was given to mixing (Roberts et al., 2010). Although this issue has perhaps been overstated at times for seawater desalination, discharge of brine can impact the ecology around the outfall site and, depending on the local hydrodynamics, these impacts can extend beyond the mixing zone (Petersen et al., 2019). In recent years attempts have been made to mitigate the dangers of high salinity in marine environments through the use of dispersers, although these technologies can also affect ecology (Clark et al., 2018). Nevertheless, this remains an important issue for inland desalination with no easy brine disposal options. Perhaps a greater problem for seawater desalination has been concern about the impacts of water intakes. Open intakes draw in (and often kill) marine life, from larger animals to microorganisms and larvae (Arafat, 2017). This can be mitigated using fine screens, low-velocity intakes or subsurface intakes, but these tend to significantly increase the price of desalination. This has been one of the main points of contestation over the development of desalination in California, for example. Rules implemented by the California State government in 2015 mandated the use of intake wells where possible (i.e. the best available and feasible technology), but developers have deemed these not financially viable for larger plants, as exemplified by the disputes between Poseidon Water and the California Coastal Commission over the 189,000 m^3/day Huntington Beach project. As the size and number of desalination facilities continues to grow, these issues become more substantial.

A great deal has also been written about the energy impacts of desalination. Although the energy requirements of the process have been reduced substantially in recent decades, desalination is still extremely energy intense (Lee and Jepson, 2021). This raises a number of questions around the potential for desalination to lock societies into high energy pathways, and the implications for sustainability and environmental justice of 'shifting scarcities' from the water sector to the energy sector (Yoon et al., 2018). (These issues are discussed in more detail below.) Moreover, where fossil fuel energy is used to power desalination (either directly, as is often the case with thermal desalination, or where the electricity grid has a fossil fuel component), desalination leads to a larger greenhouse gas footprint in water resources. As such, some have suggested that desalination constitutes a form of maladaptation (Barnett and O'Neill, 2010; Tubi and Williams, 2021).

The geography of desalination in the 21st century

What has occurred in the first two decades of the 21st century, then, is the global-scale proliferation of desalination as a new resource frontier. Desalination facilities have been installed in at least 180 countries, with hundreds of millions of people using desalinated water every day. Geographically, however, this global scaling of desalination has been profoundly uneven and has been characterised by 'hot spots' of development. Much of the existing capacity is concentrated in the Middle East (where countries like Saudi Arabia and the United Arab Emirates were early adopters of MSF and MED technologies), North Africa, East Asia, North America, and western and southern Europe; sub-Saharan Africa, Central Asia, and South Asia, on the other hand, have very little desalination capacity (Figure 5). There are also interesting geographical trends in the use of desalinated water. Large-scale desalination plants in the countries around the Mediterranean and the Arabian Gulf are predominantly supplying water to municipalities and utilities for domestic and commercial consumption, while plants in China, Chile and Brazil more often fulfil the industrial need for water (Figure 6).

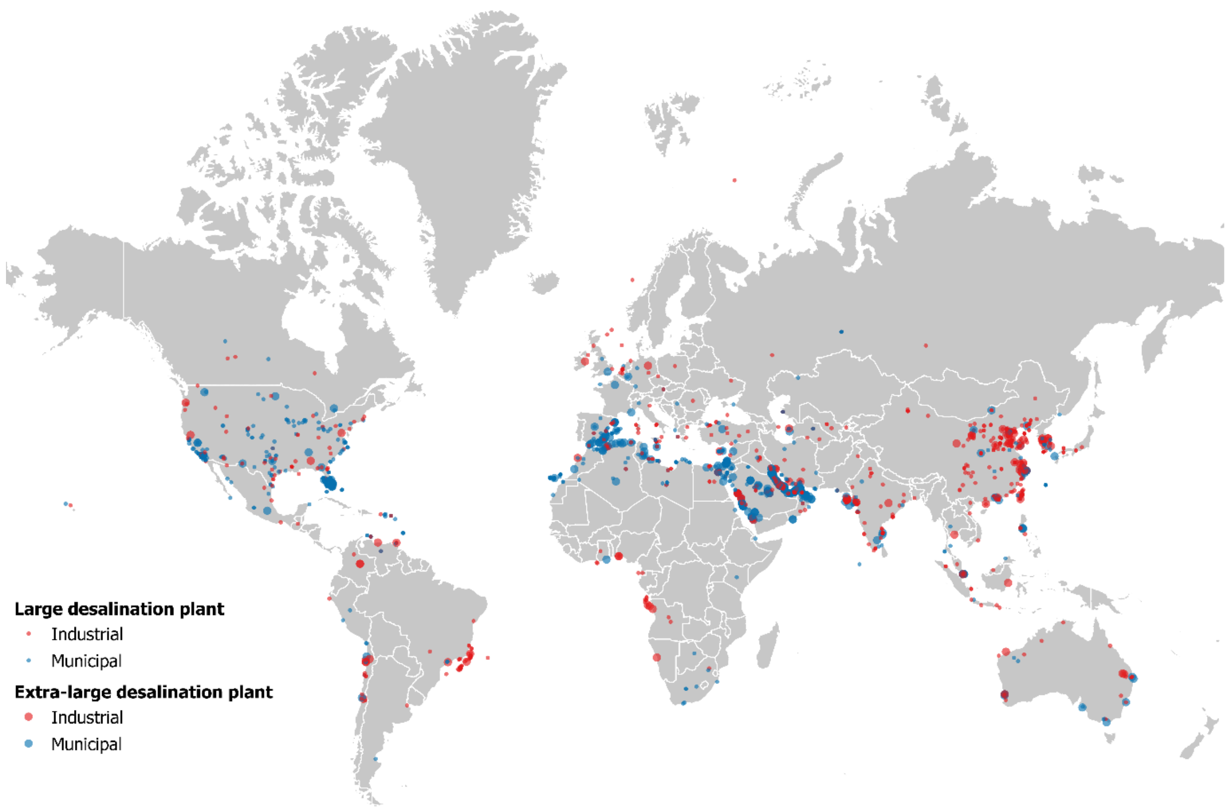
Figure 5. Online and presumed-online desalting capacity in each macro-region, categorised by plant size.



Source: GWI DesalData (2021).

Note: S = under 1000 m^3/day; M = 1000 to 10,000 m^3/day; L = 10,000 to 100,000 m^3/day; XL = over 100,000 m^3/day.

Figure 6. Large (10,000 to 100,000 m^3/day) and extra-large (over 100,000 m^3/day) municipal and industrial desalination plants.



Source: GWI DesalData (2021).

There is, therefore, a dynamic relationship between *global* processes towards the enrolment of nontraditional water resources in creation and transformations of hydro-social territories, and the particular economic, political, social and physical contexts of those territories that foster (or otherwise) the rollout of desalting technologies. The purpose of the next section of this paper is to explore how we might critically understand what is shaping the uneven globalisation of desalination.

WHAT IS DRIVING DESALINATION? MAINSTREAM EXPLANATIONS

The debate on desalination so far has been overwhelmingly dominated by technical and narrow managerial issues. Jones et al. (2019), for instance, conducted a quantitative analysis of 16,500 scientific papers on desalination published since 1980. They found that 72% focused on technological aspects, with just 7% concerned with sociopolitical factors. Of this small percentage, most considered sociopolitical factors in managerial cost-benefit terms, with only a tiny subsection developing critical or indeed radical perspectives. Within the techno-managerial literature there is an astonishing consensus – reproduced in various forms – around the drivers of global desalination (for recent exceptions, see Ibrahim et al., 2021; Montano et al., 2021). These include water scarcity, uncertainty resulting from global climate change, growing consumption caused by population growth and industrialisation, and the technological advances that have reduced the price of desalinated water, making it more competitive with other sources.

In response to this consensus of explanations, Feitelson and Jones (2014) compare the rollout of large-scale desalination infrastructure with data on water scarcity, population growth and water affordability. They find that population growth (particularly through urbanisation) and affordability of desalinated water have *some* statistical significance, but not enough to explain the rapid proliferation of large-scale desalination around the world. They also argue that there is only a weak relationship between physical scarcity of water and the uptake of desalination, and they suggest that we must therefore look beyond neo-Malthusian and classical economic explanations. This is not, of course, to say that water scarcity is unimportant or that it is not a growing challenge. The Intergovernmental Panel on Climate Change (IPCC) has been issuing stark warnings on the effect that climate change is having on water resources, water security, and the vulnerability of water infrastructure (IPCC, 2022). They signal severe challenges to water systems, particularly in places that are already vulnerable to water stress. It is also undeniable that water scarcity is a day-to-day reality for millions, particularly in the Global South. It is impossible, however, to separate out the lack of adequate water as a physical condition from the social and political factors that determine how water is used and distributed. Indeed, given that supply drives demand for water (as well as the other way round), it is important to not see desalination simply as a response to scarcity in a linear way.

Perhaps more importantly, it is also necessary to understand how scarcity is mobilised as a political and discursive strategy in order to justify new desalination facilities. Scarcity is a powerful and emotive idea that is routinely used to legitimise certain approaches to water management and the development of new infrastructure, while obscuring the economic and political interests that such interventions serve (Al-Aghbari, 2021). This is what Kaika (2003) calls the "social construction of scarcity." While the work of Feitelson and Jones (2014: 1048) offers an important critique of these mainstream explanations and assumptions about desalination, their rather vague subsequent claim that decisions to build desalination facilities are "mediated by political factors" requires much more sustained and rigorous exploration. We now turn our attention to alternative explanations in more detail, focusing first on political and then on economic factors.

WHAT IS DRIVING DESALINATION? ALTERNATIVE EXPLANATIONS

Practising hydropolitics

One of the key features of desalination as a 'new' source of fresh water is that it has the potential to transform – or realign – the social and political relations that have traditionally shaped the governance of water resources and services. At a basic level, by "turn[ing] the downstream riparian into an upstream party with regard to produced water", the exploitation of new water resources via desalination can alter the fundamental geography of water and its attendant social structures (Feitelson and Rosenthal, 2012: 283). In addition to reconfiguring power relations between existing actors, desalination is also bound up with the introduction of new actors and interests into the hydrosocial sphere. There is a close relationship between the emergence of desalination as a major new hydrosocial technology and the construction and exercise of political power (see Gorostiza et al., 2017; McDonnell, 2014; Swyngedouw, 2013). Drawing on the concept of technopolitics (see Hecht, 1998), it is therefore essential to critically understand the political interests served by desalination technologies and the political goals achieved by their uptake as key drivers of the desalination phenomenon. In most contexts, desalination is a relatively new technology, and the relationship between this technology and hydropolitics has developed over only the last 10 to 20 years. In the Arabian Peninsula, however, the technopolitics of desalination has had a more complex history. Al-Aghbari (2021) traces how desalination has been a central part of the emergence of the modern state in Bahrain over nearly half a century. Here, desalination is intricately bound up with state-building efforts and the continued assertion of state power, authority and legitimacy.

In diverse contexts around the world, desalination has become a strategy for politicians and water managers to recast hydropolitical relations and to circumvent the disputes and deadlocks that often beleaguer traditional water resources. In Singapore, for example, wastewater recycling and seawater desalination have become increasingly central to the government's strategic desire since the 1980s to reduce dependence on Malaysia for water (Usher, 2018). Being a small island with limited surface or groundwater resources, Singapore has historically relied on water imported from the mainland through the Johor pipeline, which has long been a bargaining chip in disputes between the two countries. Desalination for Singapore, then, has never been simply about increasing water supply, but has always been hyper-securitised and nationally strategic.

Spain is another intriguing example of the attempted use of desalination to realign hydropolitics by circumventing contested terrestrial resources. In 2004, a major new policy called the Programa AGUA was launched by the newly elected government. The aim of the policy was to cancel a series of planned projects to transfer additional water from northern Spain to the semi-arid southern and coastal regions, which were experiencing burgeoning urban growth (Morote et al., 2017). These water transfer plans had received sharp criticism from a variety of stakeholders, including environmentalists who were concerned about new infrastructure in delicate riparian ecosystems as well as a broad coalition of actors in the source regions. The new policy sought to implement a series of large desalination projects in order to replace the water that would have been available through the transfers. In doing so, desalination was explicitly presented as a solution for all entrenched water challenges (March and Purcell, 2014). Although never fully implemented, Programa AGUA shows how desalination was pursued as a technical fix that would diffuse political tensions between different regions of Spain and as a way to construct a new era of water abundance.

These examples illustrate what Swyngedouw and Williams (2016) call "depoliticization via desalination". In the Singapore example, desalination has undergone a process of securitisation – in the Copenhagen School sense of the word (Buzan et al., 1998) – because framing it as an issue of national integrity and security has removed the country's water supply from the realm of normal politics. In the case of Programa AGUA, desalination was used as a way to frame water in a purely techno-managerial, supply-side manner that overlooked or silenced dissenting voices. Indeed, there is a growing literature in this area that sees desalination and the techno-managerial, supply-oriented and neo-Malthusian discourses that often accompany it, as a mechanism for excavating the political from the spheres of water management (Campero et al., 2021; Speckhahn and Isgren, 2019).

While some critical scholars have argued that desalination provides a mechanism for depoliticising hydropolitics, others have taken a more positive view, suggesting that the production of new water can offer a route to greater cooperation. There is an emerging body of work, for example, that calls for the use of desalination as the basis for peace building between Jordan, Palestine and Israel. Much of this discussion revolves around initiatives by the group EcoPeace and their work with academics and activists across the three countries on the Jordan River. EcoPeace have proposed what they call a Green Blue Deal for the region, which is based on transfers of desalinated seawater and solar energy. Put simply, the idea is that Israel and Palestine have coastlines suitable for desalination, while Jordan has huge potential for solar energy generation but lacks a coastline, thereby creating potential for mutually beneficial water/energy transfers among the three countries. The Green Blue Deal envisaged by EcoPeace is based on the principal of "harnessing the sun and the sea to create region-wide desalinated water and energy security for all", and foregrounding the "importance of diplomacy in the water and climate fields as an effective tool for conflict resolution and peace building" (Bromberg at al.; 2020: 3). Similar arguments have been made about the much-heralded – but so far beleaguered – Red Sea-Dead Sea Conveyance (RSDSC) Project; it proposes using solar energy to power the desalination of water that would supply Jordan, Israel and Palestine, and then transferring brine reject from the desalting process to stabilise the Dead Sea (Walshot et al., 2020). Katz and Shafran (2020) argue that by connecting water and energy with diplomacy, initiatives like this create "issue linkages" that help avoid the zero sum politics that often dominate transboundary water management and that have certainly characterised the Jordan River basin for decades.

Some argue that the fact that desalination can increase the *overall* supply of water, irrespective of climate and rainfall, makes it a potential game changer in transboundary hydropolitics. "Just having the option of desalination", Avirim et al. (2014: 621) contend, "changes the relative bargaining power of parties and their incentives for cooperation". As such, they argue, the development of desalination can shift the context of water basin management, change relationships between upstream and downstream actors, and can potentially alter the course of diplomacy (Katz, 2021; Walschot, 2018). Similarly, Teschner et al. (2013: 100) argue that desalination has fundamentally transformed the hydro-regime in the region in ways that have had far-reaching effects and have, "altered the balance and tradeoffs between issues, actors and driving forces that had been deadlocked". It is important, however, not to overstate the transformative potential of desalination in this regard. It does not, for example, help resolve any of the underlying tensions in water management, such as rights and access to aquifers and to the Jordan River water, which have long been in dispute. Indeed, despite the initiatives noted above, Katz and Shafran (2020: 304) concede that, so far, "even large-scale desalination has not changed the overall dynamics of Israeli-Palestinian water issues". Moreover, there is even potential for new tensions to emerge as a result. The rollout of desalination could, for instance, be read as an attempt to transform Palestinians into paying water customers while simultaneously disavowing their claims to a greater share of the Jordan River. Israel's "turn to the sea" has opened up potential for cooperation, ; however, it has also allowed the country to enhance its position relative to its neighbours in terms of technological and infrastructural development, resource independence, and economic dominance, thus further entrenching asymmetric power relations in the region (Teff-Seker et al., 2019).

Decentralisation and the decline of the modern hydraulic state

The emergence of desalination, particularly in the 21st century, is inextricably bound up with changing paradigms of water management. In particular, March (2015) argues, that desalination is presented as an alternative to large, centralised and basin-based water infrastructure synonymous with the modern hydraulic state (see Linton, 2010), on the one hand, and the integration of new actors into the water sector synonymous with the shift from a 'management' to a 'governance' framework (this is explored in more detail below on the theme of financialisation), on the other hand. Desalination plants, despite often requiring considerable capital expenditure, do not have the large footprint of, say, a dam and reservoir, and can avoid the necessity of top-down coordination and inter-regional cooperation of water transfers and riparian management. They can be bolted on to existing supply systems or form the basis of new networks, depending on context, and are attractive to water managers because they offer a degree of perceived flexibility in uncertain or contested situations. The partial, and by no means even, "collapse of the hydraulic paradigm and the move toward water governance" has therefore "opened the doors to alternative water technologies" (March, 2015: 232).

Notwithstanding, desalination occupies a somewhat contradictory position as one such alternative technology. While certainly being implicated in shifting paradigms of water management, it also represents a supply-side, fixed capital-intensive strategy of water provision with serious socio-environmental impacts. Moreover, while desalination projects facilitate the introduction of new actors, the development of (particularly large) plants still rests on state support (Montano et al., 2021). As such, Green and Bell (2019: 132) argue, the emergence of 21st century desalination in some respects echoes the 20th century hydraulic paradigm, and part of its success is because it, "fits with existing cultural expectations and patterns of relationships between cities, infrastructure and natural resources". As Swyngedouw (2013: 262) puts it, "desalination projects mark the transition from a hydro-structural to a decentralized, but still decidedly state-led, market environmentalist water framework".

Decentralisation has been a key driver of desalination, as cities and regions seek to reduce reliance on unreliable or increasingly contested shared resources such as transboundary rivers or aquifers. The pursuit of what Morgan (2020) calls "water independence" has been a major factor in the adoption of desalting technologies in a wide range of contexts. In Southern California, for example, the discursive justification for the development of desalination to supply San Diego County rested on the idea of supply diversification. Using the analogy of a financial portfolio, water managers argued that reliance on water transfers supplied by a single organisation (the Metropolitan Water District of Southern California), which supplied San Diego with most of its water throughout the second half of the 20th century, left the county vulnerable to cutbacks resulting from drought and competition with other users. Their logic was that water security could be achieved by shifting to a diversified portfolio via the development of alternative and local supplies, including desalination and wastewater recycling (Williams, 2018a).

The process of decentralisation via desalination is being taken to extremes in Corpus Christi, Texas, where at least five separate major seawater desalination projects have either been proposed by various developers and stakeholders or are in the process of getting permits (see Table 1). One of these plants has a proposed final capacity double that of the current largest desalination facility in the Western Hemisphere. These projects, which all aim in theory to enhance Corpus Christi's water security in the coming decades, are being developed by three different organisations – two public and one private – who are, crucially, all trying to secure coveted state funding. These organisations are thus, in effect, competing against each other to develop (and control) the city's future water supply. This example, while extreme, illustrates precisely what we mean by the end of the modern hydraulic state and the decentralisation of infrastructure.

These imperatives towards decentralisation and technopolitics, as described above, offer insights into some of the political drivers of the 21st century desalination phenomenon. We now turn our attention to political economy for further explanation.

Table 1. Proposed seawater desalination plants for Corpus Christi, Texas.

Developer	Location	Capacity (m^3/day)[3]
City of Corpus Christi	Inner Harbor	38,000 – 114,000
City of Corpus Christi	La Quinta Channel	76,000 – 150,000
Poseidon	Ingleside	189,000 – 379,000
Port of Corpus Christi Authority	Harbor Island	189,000
Port of Corpus Christi Authority	La Quinta Channel	114,000

Source: Elaborated from Coastal Bend Regional Water Planning Group (2020).

Capturing revenue

One of the more critical areas of work on desalination concerns its relationship to broader processes of financialisation, generally in infrastructure development and more specifically in water services. Put simply, there is an emerging literature that argues that the rollout of desalination facilities is being driven not by the need for more water but by the financial opportunities such projects present for generating stable and long-term revenue for investors. This work contributes to growing critical scholarship that examines how the governance of water resources and water services is being increasingly shaped or influenced by financial actors and motivations (Allen and Pryke, 2013; Bayliss, 2017; Purcell et al., 2019). Rather than occurring via the direct privatisation of water resources, this has often occurred: 1) through

[3] For context, the current largest seawater desalination plant in North America (and the Western Hemisphere) is the Carlsbad plant in San Diego, which has a capacity of 189,000 m^3/day.

the commercialisation of utilities in diverse contexts around the world, many of which now operate under complex ownership and shareholder structures; and 2) through financial investment in individual infrastructure projects such as desalination plants (March and Purcell, 2014).

Desalination 'factories' are particularly attractive to investors and private sector actors compared to other demand-side or supply-side water infrastructures for several reasons (see Williams, 2018b). First, they produce a commodity – H_2O – in pre-arranged quantities to a specified quality, without the potential constraints that characterise other water sources, including precipitation, water table levels, and/or disputes between different users. As such, desalination should be understood as a high-technology manufacturing process, and it therefore represents a highly commodified mode of water production. Second, municipal desalination plants, which are increasingly delivered through the public-private partnership model, are usually operating under 20- to 40-year supply contracts between the owner/operator (that is, the organisation that produces the water) and the customer (the organisation that uses or distributes the water) (Greer et al., 2021). These 'take or pay' contracts mean that the customer is usually obliged to pay for water whether or not it is needed and regardless of whether the plant is kept idle – as many of them are (see Green and Bell, 2019). As a result, desalination plants generate reliable and secure revenue for their owners and shareholders over long time periods regardless of other factors. Infrastructure projects like desalination plants connect global financial investors to water bill payers (be they households or businesses), thereby "transform[ing] the guaranteed revenue streams emanating from water's monopolistic status into a range of financial products" (Loftus et al., 2019: 6). The key point here is that desalination plants are mechanisms for capturing future value by securing revenue from water consumers several decades into the future (see Bayliss, 2017).

This raises a number of both normative and practical questions. Most importantly, it suggests that decisions to develop desalination plants rather than other water management options are being made, at least in part, because of the profit-seeking motivations of financial actors who are entering the water sector via investment in infrastructure. Writing about the Carlsbad Desalination Plant in Southern California, for example, Pryke and Allen (2019: 1327) argue that this facility should be understood as a "a site of financial innovation", whereby a single piece of water infrastructure has been "financially structured to capture added value for a range of institutional investors". The case of Carlsbad (which was awarded the North American Water Deal of the Year award in 2012 by *Project Finance* magazine for its innovative financial model) is illuminating in this regard because although public utilities in Southern California had been considering desalination for some time, the project was conceived, designed and delivered by a venture capitalist company named Poseidon, which had limited experience in water and no previous experience in California. The same process is now underway for California's other extremely large desalination project, Carlsbad's sister plant at Huntington Beach.

In the example of Corpus Christi that is outlined above, where three different organisations are competing to develop desalination plants for the city, the issue is not simply who gets to supply water, it is also who gets to secure future revenue streams from these factories. Crucially, the motives of new institutional actors entering the water sector – such as *Poseidon*, who are first and foremost answerable to their shareholders may take precedence over issues such as equity in access to water, affordability, and environmental sustainability (Loftus and March, 2016, 2019). This can be a result of financial norms and logics shaping the types of options available to water managers or it can occur via direct investment in particular infrastructure. As Ahlers and Merme (2016: 770) argue, important decisions on infrastructure and water supply are being influenced by actors "without connection to, or expertise in, the inherent complexity that is characteristic of the water sector and the landscapes [they] intend to reorder". The upshot is that desalination plants are often more likely to be developed, not necessarily in regions experiencing the most severe water stress, but where the political and economic conditions are conducive to generate financial return and where financial actors have some influence on the types of infrastructures that are likely to receive investment.

Driving growth

A crucial, but often overlooked, driver of desalination in diverse contexts has been to foster growth in particular industries and for particular economic sectors (see Domènech et al., 2013). This has occurred either *directly*, where desalination facilities have been constructed to supply water for specific functions, or *indirectly*, where desalination has provided the general water security that has facilitated growth in particular areas. Direct industrial use of desalted water accounts for a large proportion of globally installed desalination capacity, as shown in Figure 6. Industrial applications are particularly common in China, South Asia, the USA, South America and West Africa. A wide range of industrial processes require desalination, including those that need extremely pure or chemically tailored water such as the manufacture of electronics or the food and beverage industry. Desalination technologies are also used to fix pollution problems, thereby legitimising the use of certain chemicals or processes in manufacturing. An intriguing example of this is in Orange County, California. In the mid-2010s, a number of the water agencies in Orange County identified per- and polyfluoroalkyl substances (PFASs) in the groundwater. PFASs are a group of chemicals used in the manufacturing of many consumer and industrial products. Certain PFASs are known to bioaccumulate and can cause serious health effects, raising concerns about the safety of one of Orange County's main sources of water. New drinking water standards introduced by the state in 2020 forced the Orange County Water District to develop a series of ion exchange desalination treatment facilities to remove PFASs from water extracted from 59 of its wells (WDR, 2022). Furthermore, desalination is widely used in industries where traditional water supplies are unreliable difficult to obtain, such as on offshore oil rigs. Several further examples of how desalination drives growth in particular sectors merit more detailed explanation.

The first, and perhaps most obvious, is the water sector itself. Over the last two decades, the desalination market has grown rapidly and steadily, a trend that is forecast to continue over at least the next decade (Birch and Weaver, 2020). The industry is highly internationalised, with tendered projects typically receiving bids from a range of globally active companies. Indeed, the desalting industry is dominated by a small number of international corporations that seek out lucrative project opportunities. (The top companies, by awarded capacity, are listed in Table 2.) As more and more cities, regions and countries turn to desalination, the industry is increasingly seen as a frontier of new accumulation potential (March, 2015). Moreover, in some places, such as Singapore, Southern California, Spain and Israel, desalination has become a politically significant industry. Usher (2018, 2019), for example, has shown how water treatment – specifically desalination and wastewater reuse – has become a strategic sector for Singapore authorities. The government has actively encouraged the establishment and relocation of water companies to Singapore through tax incentives and other measures because they believe the water industry is a sector where the city/state can gain a global competitive advantage and can showcase technological advancement. Desalination has therefore not only become an important source of domestic water for the island; it is also seen as a strategic industry that will further promote Singapore as a global hub of finance and technology.

There is an emerging critical literature that explores the close relationship between tourism and desalination. Desalting facilities are commonly used to produce water *directly* for the tourist industry. Indeed, of the 21,763 desalination plants monitored by Global Water Intelligence, 1452 of them service tourist facilities. This number largely reflects small and medium-sized plants that are operated by private hotels and resorts in regions without reliable water supplies. Examples include many of the island resorts in the Caribbean, the Canary Islands and Indonesia. There are further complex *indirect* relationships between desalination and tourism where regional and national water managers pursue desalination as a way to increase municipal water security, thereby facilitating the tourist industry. Yoon et al. (2018), for example, have studied the use of municipal desalination plants to service Benidorm, Spain. They find that the water demands of large hotels and the overall need for water security to support the burgeoning tourist industry are key drivers of desalination. The specific focus of Yoon et al.'s (2018) work is to quantify how demand for desalination from tourism in Benidorm during dry years creates additional burdens for the energy sector through a process they describe as 'shifting scarcities'.

Table 2. Largest suppliers of desalination by awarded capacity from 2009-2020, in order of size.

Company	Headquarters	Operations
Suez	Paris, France	Utilities, water and waste
Veolia	Aubervilliers, France	Water, waste and energy services
Doosan Heavy	Changwon, South Korea	Energy and water infrastructure
Acciona	Alcobendas, Spain	Energy and water infrastructure
Abengoa	Seville, Spain	Energy and water infrastructure
IDE	Kadima, Israel	Desalination
Metito	Dubai, UAE	Water and wastewater treatment
Hyflux (liquidated in 2021)	Singapore	Water treatment and power
Safbon	Tampa, USA	Water and wastewater treatment
HWTT (part of Bluestar)	Hangzhou, China	Water treatment
Aquatech	Canonsburg, USA	Water and wastewater treatment
Hitachi Zosen	Osaka, Japan	Energy, water and waste infrastructure
Sacyr	Madrid, Spain	Infrastructure
Wetico	Riyadh, Saudi Arabia	Water and wastewater treatment
Wabag	Chennai, India	Water treatment and services
Shanghai Electric	Shanghai, China	Energy and industrial equipment
Tedagua	Las Palmas, Gran Canaria	Desalination
Biwater	Dorking, UK	Water and wastewater treatment
H2O Innovation	Quebec, Canada	Water treatment
Hutchison Whampoa	Hong Kong, China	Technology conglomerate

Source: Adapted from IDA Water Security Handbook (2020) and company websites.

Calderón (2020) has also examined the connections between the growth of desalination and tourism. Their work on the small Caribbean island of San Andrés traces the social construction of water crisis and the subsequent emergence of a powerful discursive alliance between the government, the private company responsible for some of the island's water supply, and the tourism industry, to position desalination as a necessary and inevitable solution. Such a framing, Calderón (2020) argues, overlooks the historic inequalities in access and distribution that underpin the water crisis, and moreover, that the development of desalination has created a dual supply system, where one half of the island (the half dominated by tourist resorts and hotels) is supplied by desalination and the poorer, more rural half is excluded and must rely on beleaguered older infrastructure. Here, the coalition between water managers and a dominant tourist industry means that desalination "has exacerbated water inequalities at the neighbourhood and household level" (ibid: 309).

Finally, there is a growing literature that explores how desalination is being used to foster growth in extractive industries such as mining. Valuable research has been conducted in the mining regions of Chile, where desalination has been widely used to fuel the expansion of large mining operations. Mining companies have funded the construction of desalination plants either to supply their water-intense operations *directly*, or *indirectly* to compensate for their increasing extraction of groundwater resources (Alvez et al., 2020). In the latter case, mining companies will typically reach an agreement with the government – often through ill-defined legal arrangements or loopholes – to increase their use of aquifer water in return for supplying desalinated seawater to coastal cities (Campero and Harris, 2019). In such cases, desalination is used as a mechanism for justifying the continued and expanded exploitation of other water resources. This has created new social relations around water access. In the coastal Chilean city of Antofagasta, for example, the supply of desalinated water funded by mining companies in exchange for access to aquifers further inland has created an uneven geography of water supply. The city is now divided into areas that are supplied directly by desalination, areas supplied by imported groundwater (which has high concentrations of arsenic), and areas that receive a mixture of the two (Fragkou, 2018). This is administered and permitted through a highly technocratic and murky process that Campero et al. (2021) argue constitutes a form of depoliticisation in that it justifies problematic industrial water management practices while paying only lip service to issues of environmental sustainability, social justice and democratic participation. These examples suggest that the pursuit of new water resources constitutes a sort of desal-industrial complex, whereby desalination technologies are applied in particular contexts in order to fix older contradictions of industrial water management and to further drive economic growth in particular sectors. As Fragkou and Budds (2020: 450) argue,

> We contend that desalination thus serves as a supply-led solution to fuel the same industries whose growth has depleted drinking water sources that are now being replaced with desalinated water. Moreover, this dynamic serves to create new opportunities for capital accumulation via the production of desalinated water on the one hand, and the expansion of these industries on the other.

FUTURE DIRECTIONS

Sociotechnical heterogeneity

Critical social science research has often discussed desalination as a single entity or phenomenon. The way in which desalting technologies are deployed, however is materially – and therefore also sociopolitically – heterogeneous. I argue that more work from critical social sciences is needed in three areas. First, given that much of the work in this area so far has prioritised large-scale desalination (often with good reason – as explained in the section on large-scale RO), there is a need to understand how smaller and off-grid facilities are reconfiguring and transforming the hydrosocial cycle. There are, for example, enormous economic, environmental and political differences between a 2000 m^3/day facility and a 200,000 m^3/day facility in terms of their technical configuration, relative environmental impacts, energy supply, financing, and distribution/consumption of water. Financial models for delivering desalination can range widely, from fully private, public-private, and entirely public, to various forms of ownership and debt-carrying. Desalination plants, which sit within complex governance structures, facilitate the introduction of new actors and the changing relationships among these actors in many different ways, depending on context and on the size of the project.

Second, there has so far been a predominant focus on the sociopolitical dimensions of seawater desalination. While seawater represents over 60% of the market (as shown in Figure 1), the use of brackish water and wastewater desalination is growing. Despite using essentially the same technology, albeit with some small differences, the feedwater (be it seawater, wastewater, or brackish water) really shapes the sociomateriality of desalination infrastructures. Whereas seawater desalination reconfigures the relationships between upstream/downstream actors by reversing the water cycle, the production of fresh water from wastewater is shaped more by drainage networks and the power relations that saturate it. Moreover, while seawater varies within a fairly narrow bracket (with largely similar characteristics in terms of salinity, temperature, and suspended solids), there are huge variations in the type and characteristics of wastewater, which shape the economics, politics and sociocultural processes that mediate its conversion into a resource via desalination. Similarly, brackish water – usually saline groundwater – has distinct materialities that influence its exploitation (McEvoy and Wilder, 2012). In particular, the politics of brine disposal for inland brackish desalination, are very different from seawater because there are no simple discharge options, meaning that disposal is either more ecologically harmful or more costly (Rioyo et al., 2017).

Third, most of the existing literature has focused on desalination for municipal use and domestic water supply. With the exception of the emerging literature on mining in Chile (Campero and Harris, 2019; Fragkou and Budds, 2020), there is very little critical social science research on the use of desalination for industrial purposes. Nevertheless, industrial desalination represents a significant part of the overall desalination capacity, and therefore its political, social, economic and ecological dimensions (see Figure 6).

Desalination in the Global South

Until recently, most installed desalination capacity was concentrated in the Arabian Peninsula, the Mediterranean, the United States and, particularly in the case of industrial desalination, China. While these regions remain hubs of desalination, the last decade has witnessed the rollout of desalination on a more global, albeit still uneven, scale (Figure 6). As such, desalination plants are increasingly being developed to address water challenges in countries of the so-called Global South. With the exception of a few researchers however, the debate on desalination has largely remained focused on the industry's traditional hubs. In the coming years, it will be important to shift the debate towards a broader consideration of the transformative character of desalination in more diverse contexts. The need to better understand how desalination becomes bound up with inequalities in access to water services is especially pertinent. Indeed, it has been demonstrated clearly that where desalination has been developed as a water supply fix without broader consideration of the structural and historic challenges in the water sector, it can either obscure those challenges or exacerbate them (Calderón, 2020; McEvoy, 2014). In contexts in the Global North, where there are high levels of access to safe and reliable water services – although of course, it is important not to claim that countries in the GN do not have issues with insecure and inequitable water service provision (Meehan et al., 2020) – the connections between the development of desalination and social inequality can be difficult to trace. In contexts that are characterised by high levels inequality, however, where large proportions of the population lack adequate access to services or struggle to pay for them, these connections become more pressing and visible.

In contexts where networked water is dysfunctional or non-existent, moreover, we are seeing new forms of off-grid desalination emerge as alternatives to 'modern' networked supply. In 2020, for example, a deal was reached between the climate finance group Climate Fund Managers and the Dutch Fund for Climate and Development to finance 200 solar-powered desalination units in Kitui County, Kenya (Takouleu, 2020). The units each have a capacity to produce about 1300 m^3/day. They are being delivered by a Finnish company called Solar Water Solutions (which also receives support from Business Finland), which develops small standalone desalination systems powered directly by solar energy. These are being installed in villages in Kenya and Tanzania to purify brackish groundwater, and residents of these villages will be able to purchase desalted water from kiosks adjacent to the borehole and RO system. While there have been some technical barriers to the rollout of these systems, the company declares that the two main challenges will be encouraging villagers to purchase the water, and setting the price high enough to make the units commercially viable (Solar Water Solutions, 2021). Couched in the rhetoric of bringing safe water to poor rural areas, the use of desalination in this context is nevertheless entirely consistent with ongoing efforts to transform low-income populations into reliable sources of water payments via financialised innovations, in this case without the need for networked infrastructure.

Water transitions

Finally, I argue that critical research on desalination should adopt more of a transitions approach. Broadly speaking, the transitions concept is concerned with understanding combined social and technical change. Crucially, it is about understanding how and why sociotechnical change takes place and how changes can be directed towards more desirable (for example, sustainable, low carbon) futures (Hansen and Coenen, 2015). Similarly, the burgeoning literature on *just* transitions advocates forms of change that address inequality and injustice in the distribution of, and access to, infrastructural and resource services (McCauley et al., 2019; Newell, 2021). Much of the existing transitions literature focuses on energy and low carbon transitions, and is based on the principle that transitions analysis should look beyond individual technologies and their attendant social ramifications, to consider *systemic* transitions as inseparably social and technical (Bridge et al., 2013; Bulkeley et al., 2014). Similarly, debates on desalination should move away from a single-technology approach to consider the broader water transitions that are at play as well as their social justice dimensions.

A central idea within the transitions literature is that sociotechnical change occurs along pathways (Foxon et al., 2013). The capacities of present societies to change and adapt is shaped by the decisions of the past. Similarly, decisions being taken now about what kinds of infrastructure to build – and how, where, and for whom – will affect the way societies change and develop in the future. Once a technology becomes dominant or widespread it locks societies into certain pathways from which it becomes difficult to deviate or branch away. This is what Hughes (1983) called the "momentum" of technical systems, but is more commonly referred to as 'path dependency'. As Palm (2006: 447) explains, "the close links between the various parts of a system means that once a particular technology is chosen, it will continue to affect the development of the system for a long time". Several authors have begun to consider the path dependencies associated with a move towards desalination. Al-Aghbari (2021), for example, analyses the path dependencies created by successive rounds of desalination development in Bahrain over 40 years. They argue that, not only do the long lifetimes of fixed infrastructure shape water resources over decades, but that these infrastructures can in turn influence political discourse and 'knowledge environments', increasing the likelihood of similar interventions in the future. This, according to Al-Aghbari (ibid: 187), has created a "desal-dependent" cycle that is characterised by a "distinctive kind of positive feedback under which commitments are inherently self-reinforcing". Similarly, Tubi and Williams (2021) suggest that a shift towards desalination in water regimes may constitute a form of maladaptation by locking regions into energy-intense development pathways. Conversely, Teschner et al. (2013) point out that desalination can play a disruptive role in water regimes by opening up new hydropolitical opportunities. Given that desalination plants (particularly large-scale facilities) operate over long periods of time (PPP. contracts, for example, typically run for 20 to 40 years), the dynamics of technological lock-ins and path dependencies need to be better understood.

CONCLUSION

The growth of desalination in the 21st century as a new resource frontier has been rapid, and in some places it has fundamentally changed society's relationship to water. This phenomenon, which has largely been driven by the emergence of large-scale RO plants, has been global in the sense that diverse countries in both the so-called Global North and Global South are adopting this technology. Moreover, as global capacity has increased and as plant sizes have grown, the contradictions of desalination are becoming more visible and pressing, including their high energy demand, high cost, environmental impacts, and implications for water justice. Yet, the globalisation of desalination has also been a highly uneven process. Crucially, this unevenness – or what we might call the geographies of desalination – is only loosely connected to physical water scarcity or other 'external' factors. Instead, this paper has pointed to four alternative explanatory frameworks in order to critically understand the transformative character of desalination. First, it argued that hydropolitical factors shape where, when and why plants are developed.

Desalination in this sense is intimately bound up with the practice of political power and the pursuit of political goals via technology. Second, these facilities, which can be plugged into water networks or can operate in their absence, reflect and shape ongoing processes of decentralisation in water resource management, the changing role of the state, and the imperatives of many regions with diverse contexts to increase their 'water independence'. Third, the growth of desalination is being driven by broader processes that are intensifying the financialisation of water, the commercialisation of water services, and trends towards investment in infrastructure as sites of accumulation and profit-generation. Desalination plants are not alone in this regard, as financialisation is occurring in many infrastructure types and sectors – but the specific characteristics of these facilities, which under the right conditions can generate stable and long-term revenue, makes desalination a particularly attractive frontier for investment. Fourth, the development of desalination has supported growth in a number of other economic sectors including tourism, mining and fossil fuel extraction, manufacturing, and food and beverages.

The trends described in this paper towards the globalisation of the desalination frontier are likely to continue into the coming decades as the climate crisis worsens, water challenges (particularly urban) become more entrenched, global economic growth continues and thirsty industries expand, and capital continues to seek out new opportunities for accumulation. This process is also likely to continue unevenly and indeed to reinforce existing – and create new – inequalities. As such, there will be a continued intensification of the contradictions associated with the creation of new water resources, as described in this paper. In this shifting and hotly debated terrain, new critical research should focus on exposing and challenging these contradictions.

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