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Review

Barriers to Innovation in Water Treatment

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Abstract: While phenomenal strides are being made on the technological front, the water industry lags behind other sectors in the adoption of innovative techniques. Contributing factors include long lifetimes and costs of previous water infrastructure, risk aversion due to public health concerns surrounding water access, and low financing for innovation. While many professionals see the need for innovation, they prefer traditional tried and tested routes. Regulations may be useful in accelerating the transition to sustainable technologies. Furthermore, the literature emphasizes the role of environmental, social, and political actors, as well as their interplay in realizing innovation in the water sector.

Keywords: water treatment; innovation; desalination; infrastructure

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1. Introduction

Today, over 2.3 billion people live in water-stressed countries. The World Economic Forum cites global water crises as the biggest threat to our planet. The dismal state of clean water availability and sanitation in many parts of the world has led to water innovation being highly placed on the global policy agenda. In individual countries, even in the more developed world with high-quality water infrastructure, increased demand and restricted supplies have necessitated consideration of water from nontraditional sources, such as the recycling of wastewater [1–3] and desalination of water from brackish [4,5] and saline sources [6,7]. Water shortages have driven researchers to respond to this global threat through technological innovations in desalination and water treatment. The many books and journal articles which have been produced in this area in recent years are an indicator of technological developments in the water sector. With smart materials and increasing acceptance of artificial intelligence, researchers are also excited about the prospect of transforming the water services industry [8,9]. Frameworks for incorporating Internet of Things (IoT) with desalination and water treatment have also been explored for real-time data monitoring and analysis [10–12].

According to Thomas and Ford, there is a crisis of innovation in the water sector, which causes the industry to lag behind the average rate of development of technical change and corresponding institutional evolution [13]. What causes these seemingly defensive attitudes? How can these hurdles be overcome so that the water sector can employ new ideas actively and quickly? In this paper, we explore the barriers to water innovation by considering causes for the slow adaptation and inflexibility of the water industry. We also touch on the interlinkages between innovation and institution and what steps can be taken to diffuse innovations into the wider institutional framework. Taking a step away from science and engineering, this paper touches on aspects of innovation theory with respect to water-related technologies.

Figure 1 shows the number of scientific publications by year in the fields of desalination or water treatment research. As can be seen, there has been a rapid expanse in the volume of publications, reflecting greater research activity and public funding. But how well has this increased research activity translated to innovation in the water sector?

Much of the research conducted at research institutions does not make it to targeted end-users, with much effort at the lab scale failing to translate to the pilot or industrial scales needed for commercial realization. Whilst the failure of original research to translate into practical application is a common trend across the disciplines and is not confined to this sector [14,15], there are a combination of factors which are reasonably particular to water. The need for innovation in the water sector has never before been so pressing. Some factors that contribute to the high inertia of the water sector against technological changes are the monopolistic nature of water services, low drive to take risk, and long duration of infrastructure assets [16]. Most water utilities also have limited skills and resources. In the water sector, innovative remote solutions are more common than large-scale changes that only come about with organizational shifts. New desalination and water treatment technologies require organizational changes and new engineering and operational skills. R&D institutions must emphasize the need for technology transfer as vehemently as they create new processes and materials at the lab scale. One productive tool in this aspect is collaborating with industry partners to achieve tailored transferable solutions to real problems. Programs such as the UNESCO FRIEND-Water Program (FWP) have supported scientific research and innovation in water for decades [17].

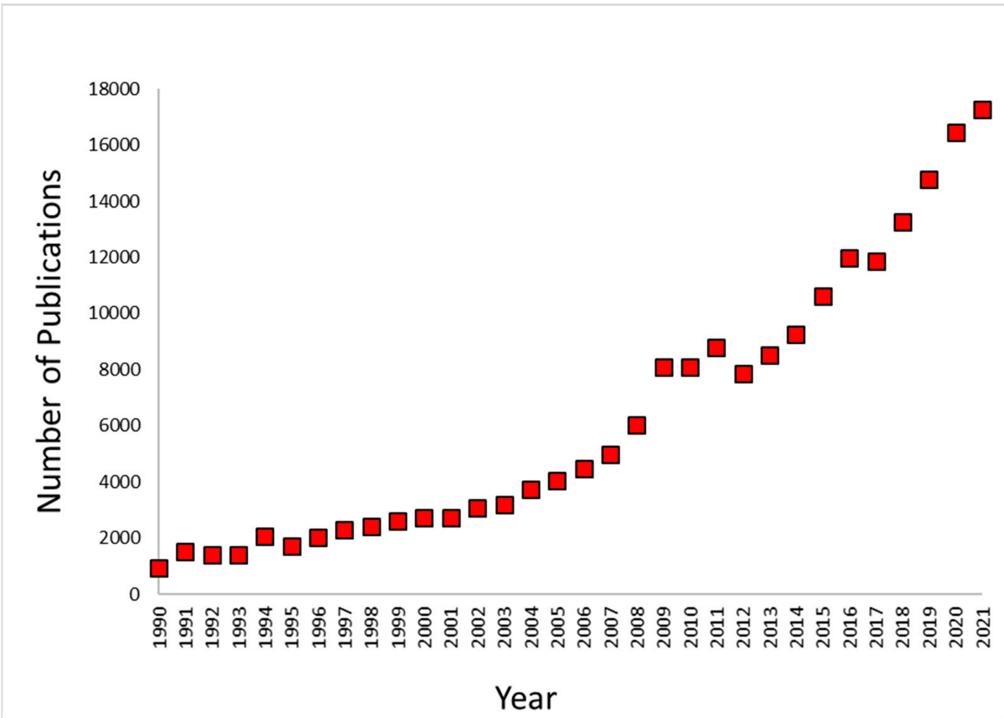

Figure 1. Number of publications in categories of either desalination or water treatment. Data taken from Scopus database, accessed 9 August 2022.

According to a 2017 survey, utility companies agreed that innovation is critical to the future of their organizations, yet less than 40% believe they are successfully weighing in on innovation to address their challenges [18]. To counter resistance against innovation, utilities are more actively engaging in innovation programs and engaging staff and external partners to develop new processes and technologies, as well as deploy advanced materials [19].

Utilities have cited cultural inertia as one of the most significant inhibitors to innovation in water and wastewater treatment. De Graaf and coworkers investigated the receptivity of professionals to innovation in the Netherlands [20]. Their study showed that urban water management professionals are well aware of technological innovations, but their involvement in projects where innovation is applied has been sparingly limited.

They also stressed that stakeholders' understanding of the potential contribution of new technologies was moderate. Mainstreaming of innovations relies on convincing these stakeholders that innovations are key to sustainable water management. Similar observations were made in California when Kiparsky et al. assessed the innovation deficit in urban water organizations by surveying wastewater utility managers [21]. Their results revealed that managers spend less time on innovation and that their perceptions may be creating disincentives to try new ideas. Cost and financing, risk and risk aversion, and regulatory compliance are the most frequently cited barriers to innovation [21]. This is understandable as access to water is considered an essential and irreplaceable service that cannot afford to fail; hence, operators and regulators are inherently risk-averse and skeptical of relatively untried and uncertain technologies [22]. This is drastically different from healthcare and energy sectors, where the end products may differ. Krozer's group added that in countries with significant fresh water reserves, dissemination of new water technologies is especially slow as there is no sense of urgency to reduce groundwater abstraction even though the threats of over usage are well documented [23]. In the Netherlands, even a tax on groundwater use which has been increased several times did not change this behavior.

2. Drivers for Innovation in the Water Sector

Before considering factors reducing innovation in the water treatment industry, we must consider what factors are driving a need for innovation in this sector, as innovation merely for the sake of innovation is not very well justified.

On the demand side, ever-increasing population growth results not only in a direct demand increase for water for consumption, but comes with greater economic activity, leading to predictions of a demand increase in excess of population growth rising at an exponential rate [24]. Whilst currently over 4 billion people are thought to live with severe water shortages for at least one month per year [25], this can only be expected to increase in the coming decades. This creates a need for both greater supply of clean water and the need for technology which can create efficiencies in the system by reducing water usage and waste. This latter can be both at the production or consumer scale and in between including reducing transmission losses due to leaks. In addition, increasing population, agriculture, and industrial activity will increase potential for pollution of water bodies, leading to need for increased treatment, and regulations.

At the same time, environmental change, especially related to global climate change, is predicted to lead to reduced rainfall and the potential for desertification of some areas [26–28]. Increased temperatures will lead to both increased evaporation rates of surface water as well as driving demand for irrigation of both food and cash crops and recreational areas. Much of the increased demand is currently serviced by groundwater abstraction, often at rates far in excess of renewal rates [29,30], leading to aquifer depletion, degradation of the local natural environments, and a need to reduce usage and or find alternative sources of fresh water, with some areas investigating recharging of groundwater as a potential mitigation strategy [31]. Alternative sources of freshwater often comprise use of desalination technologies to abstract freshwater from seawater [32,33], or implementation of further treatment of wastewater beyond current use to allow its reuse [34]. With desalination, although some areas have been desalinating seawater for some decades at a municipal scale, this is likely to increase further in the future. Very high energy and capital costs for desalination infrastructure have made this unattractive in the past, but innovation, such as development of desalination by reverse osmosis (RO), has brought energy costs much lower, increasing their attractiveness. However, costs are likely to remain much higher than for abstracting fresh surface water, and there are a number of environmental questions still to be fully answered, such as what to do with the quantities of concentrated brine produced as a byproduct [2]. With regards to reuse of treated wastewater for municipal supply, the technology exists and has been implemented in Singapore [35], but has not been widely adopted elsewhere. Here, regulators and the wider public need assurance that any such water would be safe to use, with recycled wastewater for human use seen as unfavorable to consumers [36,37].

Speight [38] carried out a survey of private UK and municipal US water utilities and found that the factors which best helped to drive innovation were a supportive culture of innovation within the water companies themselves; a regulatory regime which valued and promoted innovation; the capital available to spend on research and innovation activities; and the backing of the public to make changes. Furthermore, Speight noted that businesses focused on business models, such as private sector utilities, focused too much on financial considerations, whereas public owned utilities focused too much on political considerations.

3. Status of Water Innovation

Innovation differs from invention in that the latter is the creation of a previously unknown idea, whereas innovation is the process of invention combined with its conversion to useful application, i.e., commercialization and practice that would drive a change in markets and society [39]. In innovation, technical contribution takes a backseat as commercial development, application, transfer, and diffusion of the technology's outcomes dominate. A relevant example of this is the invention of RO by Loeb and Sourirajan in 1963 when they developed polymeric membranes which were suitably tight to restrict the flow of salts through water permeable membranes. The corresponding innovation took place decades later in the 1990s when the first large-scale RO desalination plant was built [40]. It is important to make this distinction to elucidate the barriers to innovation in urban water.

Innovation can be transformative or incremental. Incremental innovation brings about small improvements to specific areas, whereas transformative innovation, as the name suggests, introduces a significant shift or change to processes or technologies [41]. Considering the same example, while desalination was introduced as transformative innovation, over time incremental technical improvements, such as the use of energy recovery devices, high pressure pumps, etc., have led it to become an established technology [42]. Despite dramatic investments in research and innovation, the water industry lags in implementing innovative techniques. Experts attribute this slow adaptation to the conservative nature of the industry [13]. In fact, the term "water innovation" had not even appeared in the published academic literature prior to 2004 [43].

While researchers often view water management as a technical issue, implementation of solutions are heavily impacted by governance. Due to the involvement of several institutional actors, any technical solution requires weighing of interests, values, and cooperation [44]. Innovative concepts in water are a combination of technical, organizational, and institutional. Eshuis and van Buuren provide a fascinating insight into time as a factor that affects development of innovation in water: alignment of timeframes is absolutely critical in realizing water innovations [45]. A similar transitions perspective was employed by Quezada et al. to reveal tensions between industry reform and environmental policy [46].

Water infrastructure consists of large-scale engineered systems that may include water treatment facilities, desalination plants, dams, reservoirs, aqueducts, and pipelines. Water infrastructure systems are typically designed with long lifetimes of 50–100 years [47], which also contributes to stagnation in implementing new technologies and predisposes the water industry towards incremental changes as opposed to pioneering or transformational shifts. Urban water infrastructure systems are influenced by many different stakeholders: water consumers such as households, public and private water producers and operators of plants, producers and sellers of technical parts, as well as industry and trade [48]. Such large technical systems typically exhibit a dominant institutional, as well as technological, lock-in effect, especially as many of the technical components are designed to have long lifespans and have large sink costs. This results in strong resistance to drastic changes in urban water systems. The water industry often prefers to employ traditional and tried methods over new, unconventional technologies. For example, although reverse osmosis has surpassed thermal desalination in many parts of the world due to its proven low operational costs, this has not been the case in countries that lead global desalination such as Saudi Arabia and the United Arab Emirates. Although there are other factors, existing infrastructure for thermal desalination, often built as part of cogeneration plants, is one reason that the transition has been sluggish. The inflexibility of existing water infrastructure has led water services to identify alternative approaches and transition to more sustainable systems.

Another contributing factor is that the water industry seldom conducts its own research and development and instead relies on external research institutions or supply chain companies to carry out research activities. Dominguez et al. explain that water utilities have not invested in in-house strategic planning, which, when left to external parties such as consulting engineers, leaves little room for technological and organizational innovation [49]. This further diminishes potential for innovation and subconsciously provides support to established technologies and organizational structures. To place this into perspective, in the UK, water companies invest less than 1% of their capital expenditures on R&D [50]. Similarly, a very small portion of water companies in the US are members of primary research foundations such as the Water Research Foundation and the Water Environment Research Foundation [38]. In the Netherlands, R&D expenditures in water management have steadily decreased between 1992 and 2002 [23]. Unlike many technological fields, a culture of innovation is lacking in the water sector due to their limited direct participation in research and the prioritization of other goals. Water utility companies place public health and provision of water services above innovation. To ensure public health, water service providers are constrained by strict water quality regulations for drinking water as well as for safe disposal of waste streams. Furthermore, depending on whether the company is for-profit or municipal, other goals that may take precedence over R&D are financial considerations and/or the backing of political initiatives [51]. This leaves innovation at the lower end of priorities, which is not likely to change without external pressure. It is thus suggested that regulatory bodies play a role by providing support for innovation and assisting companies in building a culture of innovation.

Ajami et al. [51] listed the main management and policy barriers to water innovations as a combination of low water pricing rates; regulatory restrictions; the absence of regulatory incentives; lack of access to capital and funding; limited data on public health and risks which come with new technologies; geographical and functional fragmentation of the industry; and the long lifespan of water systems. Furthermore, Speight noted that businesses focused on business models, such as private sector utilities, focused too much on financial considerations, whereas public-owned utilities focused too much on political considerations [38].

4. The Role of Water Pricing

In many countries, water is underpriced, as the cost of extracting, transporting, filtering, and distributing water is often subsidized. This underpricing means that suppliers are not always able to replace aging infrastructure. In addition, the pricing of water does not take into consideration the opportunity cost of water extraction, i.e., reduced recreational opportunities or environmental destruction in the form of biological harm to aquatic ecosystems, etc. Underpricing of water leaves little revenue for suppliers to invest in innovation. Water supplies account for the highest ratio of capital investment to collected revenue compared to other utilities such as electricity, gas distribution, telecommunications, etc. Not only does this make it difficult for water suppliers to keep up with new infrastructure, but even replacement of existing infrastructure presents a burden. An unfortunate example of this is the Flint water crisis which saw high levels of lead in the city's drinking water due to leaching from aging pipes [52]. The percentage of water lost to leaky pipes varies between 7–50% for developing and developed countries [53], which is wasted energy that leads to reduced revenue. Other sources of revenue loss include metering discrepancies and unauthorized consumption. These factors translate into limited funding sources for new infrastructure and water projects [54]. Another drawback of underpriced water can be better understood by drawing parallels with the energy sector. The prices of fossil fuels have had a significant impact on the adoption of energy-efficient and renewable energy technologies, with higher electricity cost correlating with most active initiatives to support new technologies, in addition to policy backing. Water is simply not priced the same way, which lowers incentive to innovate and implement new technologies. As climate change has driven innovation in the energy sector, the water sector is also slowly moving towards a more risk-accepting position through collaboration of public, private and civil entities. Singh echoes these sentiments and believes that our "scientific awakening" to face energy challenges can guide us when it comes to the current global freshwater crisis [55].

5. The Role of Regulations

The introduction of regulations can help support innovation in water treatment and desalination technologies. As an example, governments can encourage water-recycling which would force the growth of wastewater treatment technologies, encourage its diffusion and improvement, as well as facilitate the development of more cost-effective technologies. Similarly, regulations on the salt content of disposed waste desalination brine will give rise to the implementation of brine treatment, disposal, and even mining technologies [56–58]. On the other hand, regulations can also restrict innovation. Regulations regarding the environmental hazards of nanomaterials may hamper or restrict the use of nanomaterials for membrane development to specific structures, or it may encourage further studies in understanding the environmental impact on aqueous environments of using electrically conductive membranes and spacers with nanomaterials.

Often, an explosion of patents in a certain technology can be observed when the EPA has imposed technology-forcing regulations [59]. Nevertheless, mature industries such as water treatment and desalination can be less receptive to regulatory requirements that impose innovation. In addition, regulatory approvals can be a deterrent for new technologies entering the market. Spiller and coworkers showed that regulation with respect to drinking water and/or environmental standards can stimulate innovation, but only under specific organizational, natural physical and regulatory conditions [60]. They developed an integrated framework to enable the analysis of innovation process and factors, particularly in the English and Welsh water sector, and identified twenty factors that affect the five stages of environmental innovation through research interviews and the literature. While the technological aspect has been studied in much detail, the role of policy in the water field has been extremely limited. Reforms in water management require technological innovation combined with social, political, economic, and behavioral changes [61,62].

Many water systems in the US are on the verge of a Flint-like water crisis as they are urgently in need of repairs, upgrades, and replacements, but limited funding makes the situation dire. In 2014, the Congress approved the Water Infrastructure Finance and Innovation Act (WIFIA) to combat this problem [63]. WIFIA is a five-year pilot program that focused on supporting underserved large-scale projects through low-interest financing [64].

According to the diffusion of innovation theory mapped out by Rogers, an initial few are at first open to a new idea and adopt its use. They then spread the world and allow the innovative idea to diffuse amongst the population as acceptance is gained. In later stages, the sector reaches saturation and the rate of adoption decreases. He categorizes five types of adopters of any innovation as innovators, early adopters, early majority, late majority, and laggards [65,66]. Figure 2 shows Roger's estimated percentage of each category in the process of innovation diffusion. The factors affecting diffusion of innovation need to be better understood for policymakers to stimulate innovation within the water industry.

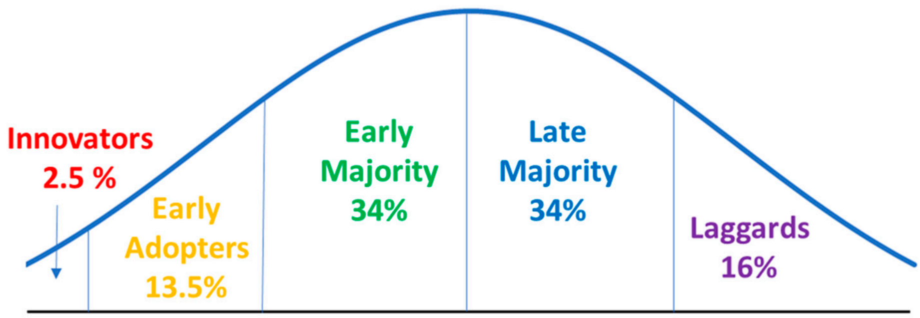

Figure 2. Stages of adoption of an innovation, according to Roger's classical diffusion of innovation theory [66].

Diffusion of innovation can be assessed through various indicators, such as total installed capacity, market share, patents, or bibliometric indicators [67]. The literature shows that innovation is a result of the interactions of various players such as research institutes, regulators, civil society, and end users in varied setups or network structures [67], rather than corresponding incentives of these players as part of an "innovation system" [48]. Thus, a technological innovation is much less the technological component, but more so the complementary role of institutional structures that allow transformative innovations to succeed. More than the hardware itself, it is the stakeholders, networks, and institutions that foster the introduction of innovative systems.

6. Other Barriers to Innovation

In the public sector, the most reported barriers to innovation are organization-related, i.e., administration of process [68]. Interaction barriers that include relationships of public sector organizations with other institutions and citizens for efforts in delivering innovation are the second-most prominent category of barriers. Despite an unsupportive institutional environment, interviews with high-ranking officials in Northern Italy wastewater utilities showed that resources could incentivize firms to take on innovation [69]. The same study also showed that residents and local businesses can exert external pressure on water utilities to advance or deter the implementation of innovative solutions. Lee et al. reviewed drivers and barriers to urban water reuse, suggesting that while external environmental shocks such as droughts can catalyze innovation in water systems, any transition depends strongly on geographic factors combined with economic, regulatory, and political alignment [70]. They identified governance, technology, and water source as three relational dynamics that may aid policymakers and researchers in transitioning water systems and nurturing innovation in the water sector.

In the implementation of novel membrane technologies, energy costs and environmental constraints are still considered bottlenecks [71]. In arid regions, well-developed membrane technology for desalination and water treatment must be supported by appropriate organizational structures to provide social, economic, and environmental relief to the population. As an example, many countries opt to use sand filters instead of switching to membrane technologies, despite the proven advantages of the latter. However, apart from assessing decreased risk to public health and greater space efficiency, operators would need to consider retraining their workforce and creating a new supply chain for components of the membrane system. Similarly, the widespread implementation of desalination processes would carry political and social implications beyond its technological benefits. Even incremental innovations such as real-time leak detection techniques and energy-recovery devices are only slowly being adopted, despite proven increased energy efficiency owing to lack of familiarity, tradition, and risk aversion.

Kiparsky et al. argue that there is an innovation deficit in urban water management, emphasizing the need to expand our definition of innovation to sociotechnical innovation rather than new technologies alone [40]. Technological innovation is certainly not the only challenge here, as one can judge by the plentiful literature available in this area; it is the interrelated adaptation between technologies, firm strategies, and institutional structures. Industries and water boards have not exploited the modern tools and techniques available to them. Smart, integrated technical solutions will be attractive to stakeholders as well [72].

7. The Way Forward

As long as water professionals themselves lack a sense of belief in innovation, the future of innovation in water remains stagnant; it is therefore vital that innovative solutions target the organizational culture of water management entities to enhance association and acquisition of new technologies. This finding was confirmed by Anne M.J. Hyvärinen et al. in the context of Kenya [73]; they suggested that proactive utilization of partner networks is critical to managing resource-constrained innovation uncertainties. Beyond technical know-how, enabling and implementing innovative solutions requires connecting different players. Fragmentation of innovation systems, lack of scale-up capital, absence of municipal support budget, and adoption costs are some of the main bottlenecks to water innovation in Africa [74,75]. Gabrielsson et al. investigated the Water Innovation Accelerator, a virtual-network-centered incubator model implemented in Sweden, as a means to aid the development and market uptake of water-related innovative solutions [76]. Their work suggests that such an incubator can bring together public and private stakeholders with different levels of assets and competencies through an entrepreneurial network through which network-embedded innovation opportunities can be identified and supported. Their study was intended to assist researchers and incubation managers, as well as policymakers, in their efforts to accelerate water innovation. In the context of China, Cheng and Hu recommended that improved legal and policy framework of water rights and stronger institutional arrangements will allow effective and efficient allocation of water resources as well as improve innovation and adoption of water-saving technologies [77,78].

8. Conclusions

There is no doubt that sustainable water requires institutional changes: the burden does not lie on technological pioneers alone. The path to transition water to a more sustainable and resilient industry is rooted in awareness, education, transparency, and democratized access to information about water systems [79], and is essential to solving challenges related to water, namely, scarcity, quality, access, and affordability. First, all actors in the water sector must recognize that surface water is limited and cannot continue to be extracted under the grave pressures of population growth and climate change. Additionally, the value of water is very poorly understood and is in part responsible for the underfunding of water infrastructure and lack of innovation. The water sector can follow the transition of the energy sector towards sustainability by making available alternative technologies that are low-energy and efficient. Perhaps not in the near future, but eventually, smart membranes made of electroresponsive materials will help in this regard with real-time control strategies. Finally, while innovation in policy and technology is possible without involving the end user, their active engagement and access to water quality and quantity data will allow them to relate to the challenge and promote sustainable measures, eventually allowing the water sector to be considered renewable.

The water industry requires better compatibility between institutional structures and new technologies in order to bring about transformative innovation systems. There are many barriers to innovation in the water industry. Some stem from the high sink costs and long lifetimes of previous infrastructural investments which leave little room for fast adaptation to newer technologies. The low price of water also contributes to less capital for future investments. Second, the public health concern surrounding water systems means that there is little room to take risks. Third, regulations in place do not necessarily support innovation in water innovation, and even when they do, water utilities seldom carry out research themselves. Policies should enable the creation of services that seek innovation and adaptations as a means to contribute to the economy and move forward in addressing water issues. A possible solution is to introduce policies that facilitate startups. Some suggested changes are already being implemented, but the effects might not be noticeable for a few decades. Enablers of innovation in the water industry include a supportive culture for innovation, regulations that foster innovation, financial resources to carry out research and employ improvements, and, very importantly, public support. This chapter shows how innovation in the water industry has been hampered, and the steps that can be taken to foster it by inducing organizational change and considering technological, environmental, social, and political actors.

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