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Sustainability Research Institute

United States Water Infrastructure

From fixing leaks to regenerating the system

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About this Research

and the Sustainability Research Institute

Dear Reader,

I'm pleased to present our research on the US water infrastructure in the United States (US). This paper is published at a pivotal moment. America's water system is facing its fourth crisis in history: an infrastructure so outdated that it's acerbating already rising challenges in water availability, affordability, and its safety for consumption. For this reason, the nation's water infrastructure received the largest federal support for renewal in US history from the past administration. Now, at global environmental tipping points for climate change, biodiversity loss, and pollution, technological acceleration, and societal developments like inequality and a new administration entering the White House, the matter of improving the US water infrastructure is as complex as it is crucial to the nation's wellbeing.

The mission of the Sustainability Research Institute is to tackle precisely such pertinent and complex issues. Set up in 2020, the team is part of Schneider ElectricTM, a leader in the energy transition. With a purpose to bridge progress and sustainability for all, Schneider Electric aims to leverage its digital expertise and energy management and automation services for a just transition. The Sustainability Research Institute serves to illuminate pathways in this unchartered territory.

By leveraging scientific research as well as the technical expertise of our colleagues, and by examining the facts in their contexts of broader social, environmental, technological and geopolitical shifts happening all around us, we strive to deliver independent and actionable research that identifies drivers for systemic change. For this purpose, our experts regularly speak at forums and our findings are publicly available online.

I hope this research will bring insights to business leaders, policy makers, and citizens, that can support them in an approach to the US water infrastructure that goes beyond fixing leaks, i.e., tweaking the system, and instead aims to transform it towards what water has always been: a source of regeneration.

Gaya Herrington

VP of Sustainability Research,
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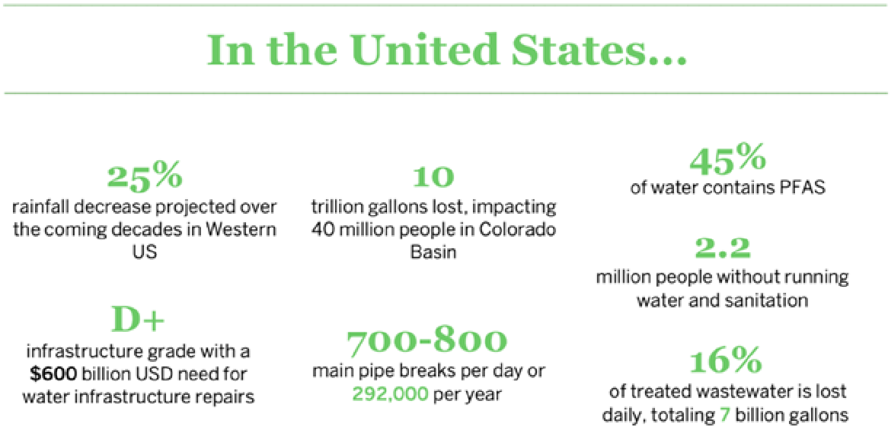
Executive Summary

Water around the world is becoming scarcer and more polluted. The United States (US) is no exception. These challenges are compounded by a highly aged US water infrastructure, and economic and social inequalities that raise issues when it comes to clean water access and affordability.

This document looks at how these environmental, technical, and social aspects interact and may point towards synergistic solutions.

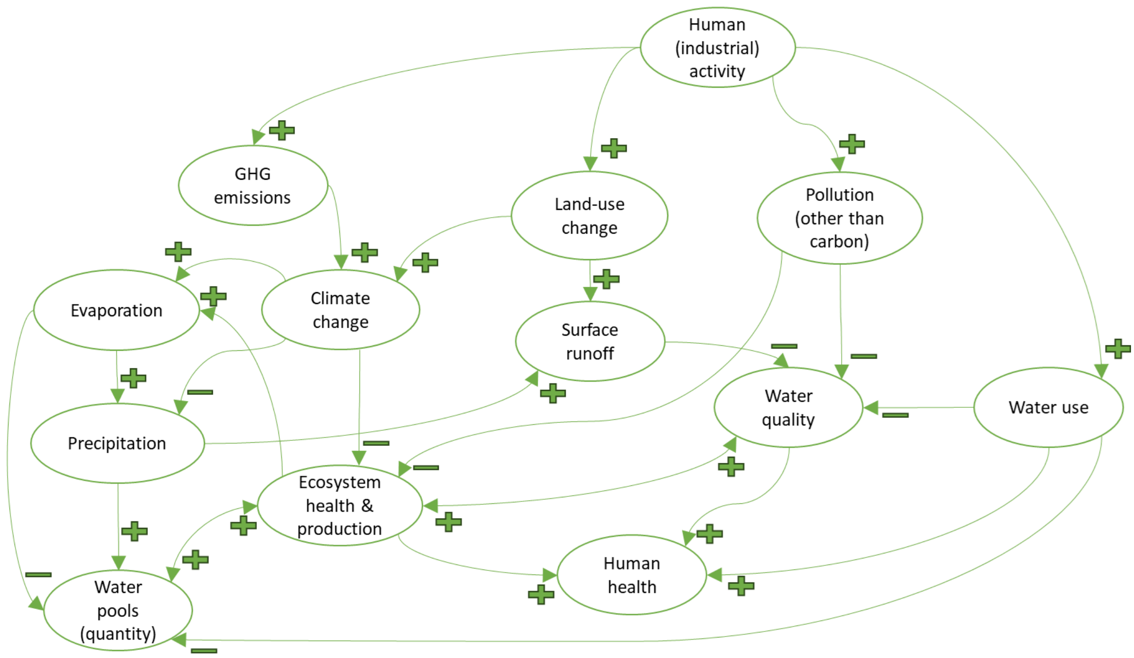
Exhibit 1. Key Statistics on water infrastructure



The environmental interactions are summarized in the first causal loop diagram (CLD) below. The CLDs are directional. An arrow with a "-"sign means that an increase in the causal factor has a diminishing impact on the factor it points towards, i.e., a negative impact, while an arrow with a "+"sign indicates a positive impact (not to be confused with a desired one). Human activity, including industrial processes, lead to increased greenhouse gas emissions, other pollution, and land use changes.

These are driving water pollution and climate change, which in turn acerbates water degradation through increased stormwater runoff, as well as water scarcity through increased evaporation and reduced precipitation. These effects negatively impact human and ecosystem health in a compounding manner.

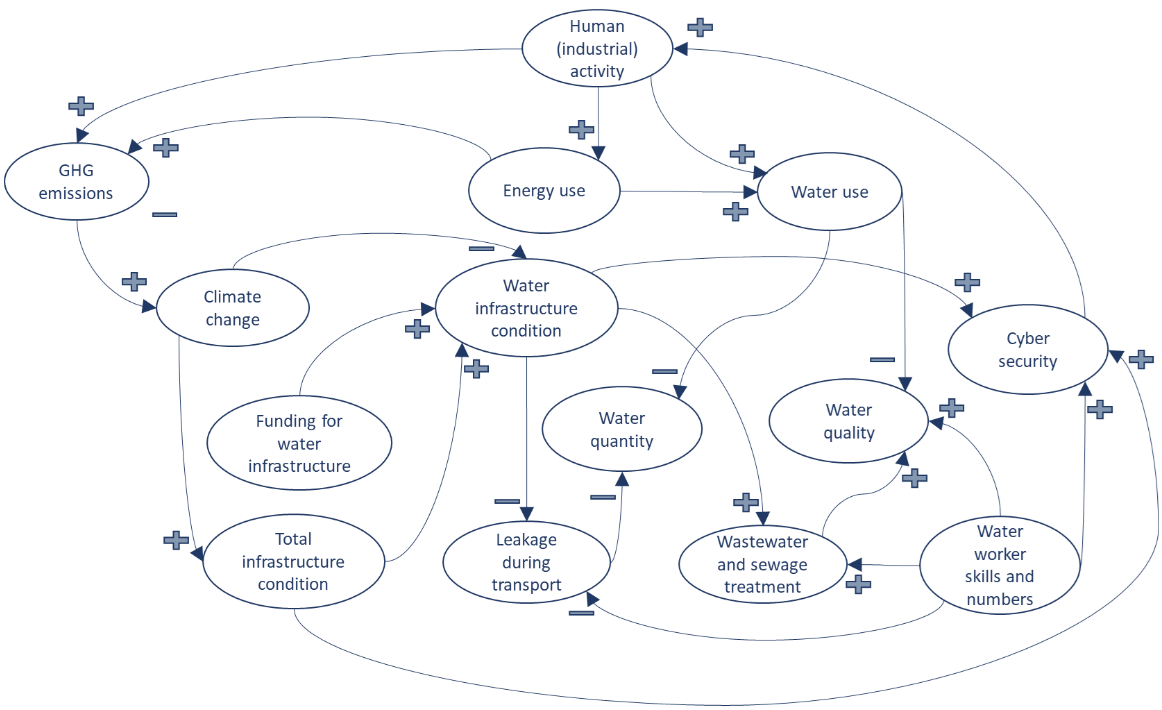
Exhibit 2. The environmental CLD.



Water quality and quantity face further pressures from a water infrastructure that is overdue for replacement and upgrades. The US water infrastructure consists of a vast, diverse, and sometimes opaque network of pipes, dams, wastewater treatment facilities, and both private and public water systems. These water systems include municipalities, cooperatives, and private industrial systems, among others. Municipalities supply by far the largest share of the population. The technical challenges these various water systems face, next to the aforementioned environmental ones of increasing water scarcity and worsening quality, are nonetheless relatively uniform: outdatedness, cyber security, and lack of funding.

About 16% of water is lost due to leakage, and that is coming on top of the water lost from about 700-800 pipes break in the US every day. Outdatedness also makes water facilities more vulnerable for cyber security attacks. Another age-related risk is the upcoming retirement of a large part of the water workforce, who might take with them a lot of valuable knowledge. These issues can be ameliorated with (new) worker trainings and proper maintenance, replacement, and upgrades to the physical water network, including with digital technologies. But the high investment costs for such projects are another major obstacle for many water systems, especially the smaller ones.

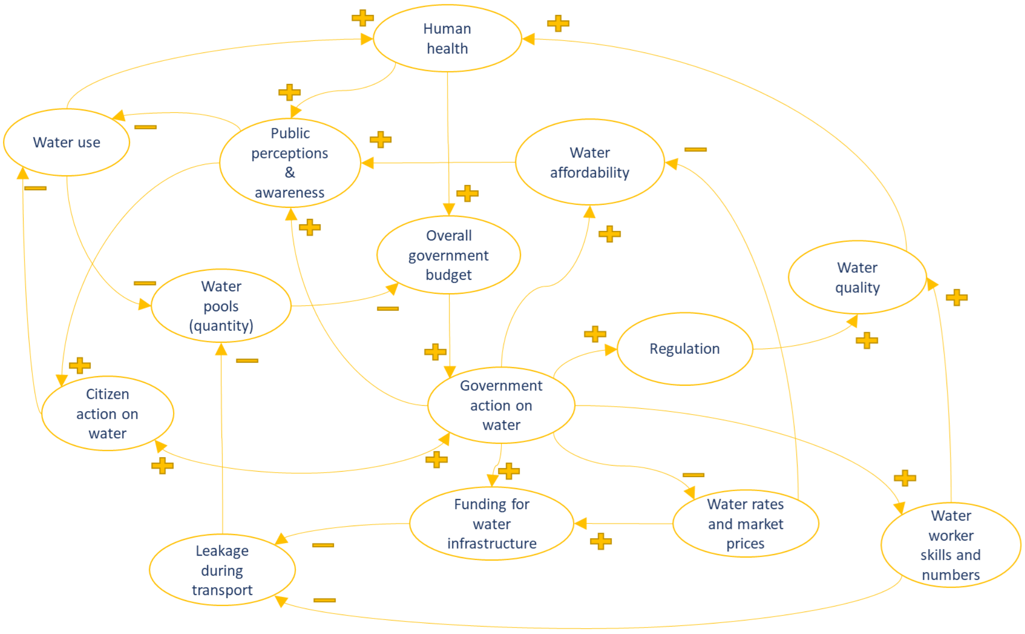
Exhibit 3. The technical CLD.



When the social aspects are concerned, we find that government, private organizations, water systems, and citizens can each play a part in improving the system in various direct and indirect ways. The government holds several crucial roles, including the regulation on allocation and quality, funding of projects through the public budget, and influencing water rates.

Affordability of water for low-income households is another issue that the government may want to act upon with special programs. Public awareness campaigns on the importance of water conservation to improve efficient use can also prove useful. At the same time, citizens can engage, and have done so, with government and politicians on water issues, which are often ranked as Americans' top environmental concern.

Exhibit 4. The social CLD.

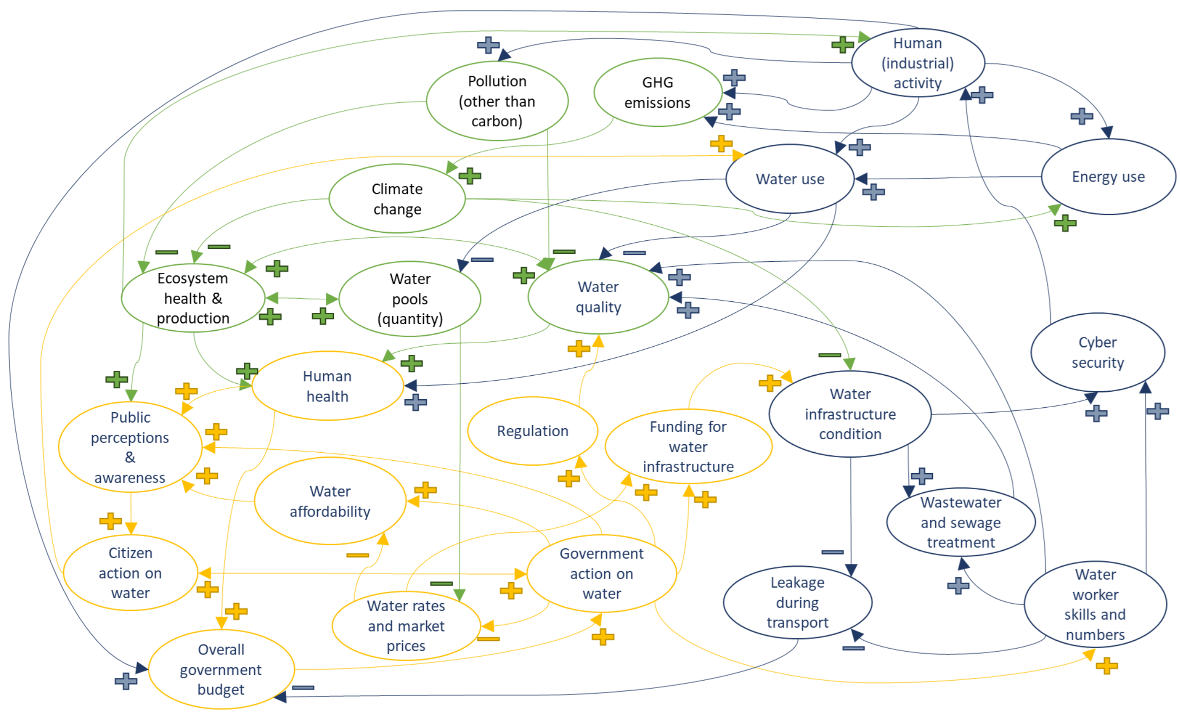


When the environmental, technical, and social interactions are put together in a combined CLD, we obtain the overview in Exhibit 5. After analysis, detailed in the last chapter of this document, three main areas appear to offer space for synergistic solutions: the government's central influence, citizen's underused influence, and the power of regenerative business models.

The government's central influence can be observed from the many connections coming out of the factor *Government action on water* in the CLD. It is a leverage point, but it also begs the question if it can be supported with more connection going into it.

That's where *Citizen action on water* comes in; this factor only has connections going out to *Water use* and *Government action on water*, i.e., as a user and voter. Given their relatively strong concern for water issues, it is worth exploring if there are ways citizens can become more active in the water system. And lastly, while Ecosystems health & production is very connected, it is so only to other environmental factors, despite several indirect and often negative influences from human activity. Regenerative action could create new – desired – connections from the technical and social factors to *Ecosystems health & production*.

Exhibit 5. The combined CLD.



Concrete examples from these three areas include: tiered water rates, nature-based-solutions, digital solutions, innovative funding instruments, and cooperation.

Tiered water rates address both the need for incentivizing efficient water use as well as the water affordability for low-income households, by setting water rates in tiers. The first tier, which is based on a specific users' needs, is set low to keep basic water use affordable. When a tier threshold is crossed, the water rate increases disproportionately, serving as a strong incentive to conserve water. Tiered water rates can thus lighten some of the burden on governments, as there might be less need for affordability programs, while providing additional funding collected from the heavy water users.

Nature-based solutions in this context is the use of natural processes and features to address water challenges. They can vary in size and scale, from a single green roof to capture rainwater and climate control, to waterfront parks consisting of permeable pavement, vegetation, rocks, plant boxes, and pebbles to help mitigate impacts from flooding, to restoration of entire ecosystems to support the natural water cycle. Design, production, and implementation of nature-based solutions are an example of what a regenerative business model could look like in practice, and because they're typically not more expensive that typical "grey infrastructure" they alleviate some pressure from governments to as well.

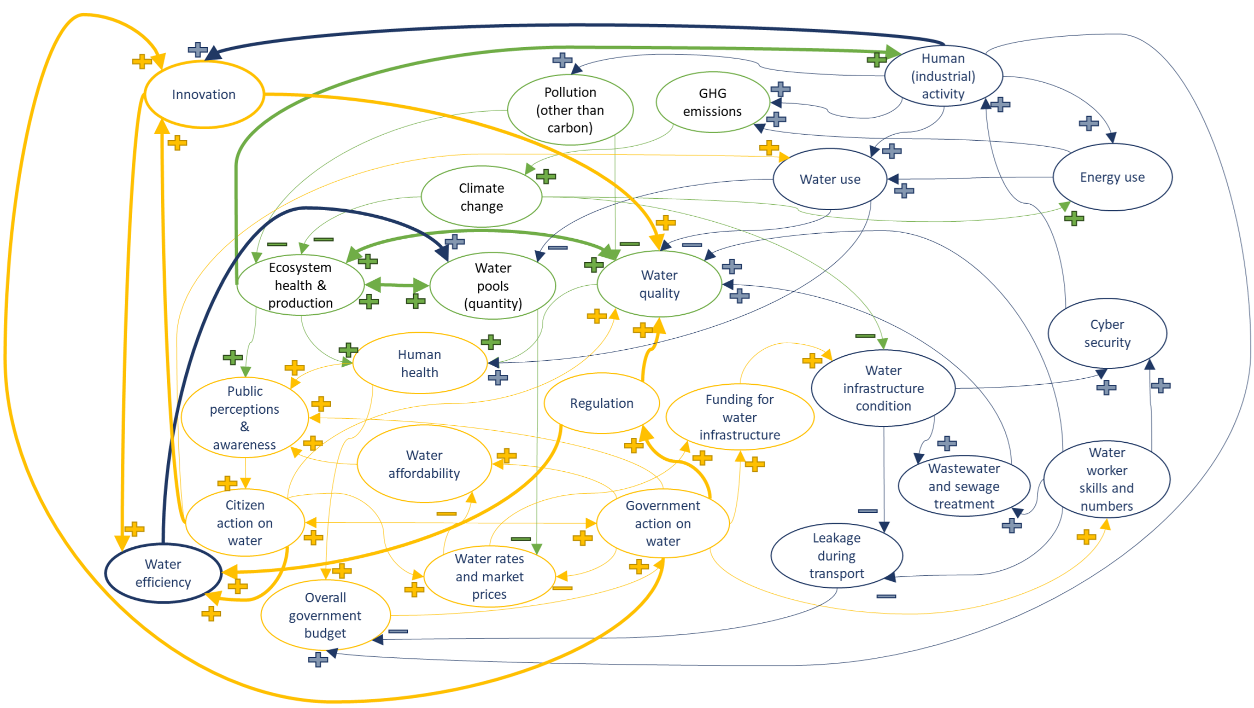
Digital solutions include remote monitoring equipment, smart sensors and meters, digital portals, meter reading technologies, AI, cloud computing, and predictive modeling, among other things. Especially when combined into digital infrastructure, they can significantly boost water efficiency, water quality monitoring, and leakage and other malfunctions detection. They can thus also be a solution in regenerative business models, especially perhaps in combination with nature-based solutions.

Innovative funding instruments can take some of the funding pressure for water infrastructure off the government budget. In the water space, they include special purpose bonds and loans, and payment for ecosystem services (PES). The first kinds pertain to large, often institutional or multinational, players and projects, like with green and blue bonds, and green loans. PES are typically funded from taxes and make ongoing payments to individuals or communities for managing their land to provide ecological services, including water-related ones. Both instruments have a solid practice record by now, including some great successes, and their use is increasing.

Cooperation is crucial to the success of any implementation. The above-mentioned solutions are unlikely to be successfully implemented without enhanced coordination between government organizations, companies, and citizens. They will need to work together towards a shared goal of enhanced water systems in the US, aligning design, planning, execution, and ongoing operation, as well as streamlining of social justice issues throughout these processes.

If these solutions, and more, were to be applied at a larger scale, the created new connections and factors would transform the CLD into the below Exhibit 6. With government, business, and citizens deliberately applying their innovative and organizational power towards serving nature, including water, the US water system could become truly sustainable. That is to say, as US water infrastructure that delivers clean and affordable water to everyone, without damaging or depleting water pools nor the ecosystems as a whole.

Exhibit 6. The transformed CLD with a "Regeneration nexus" highlighted.



Chapter 1 Introduction

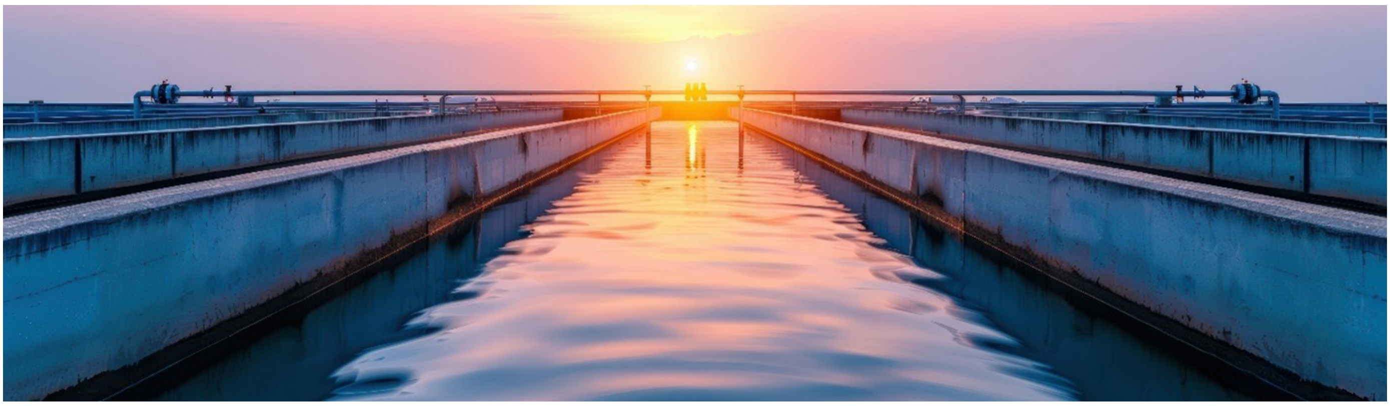
Water is key to human health and well-functioning ecosystems, societies, and economies — in short: essential for life on earth. The United Nations (UN) Sustainable Development Goals (SDGs) recognizes this in SDG 6, which focuses on ensuring safe drinking water, sanitation, and hygiene for all, aiming to secure the availability and sustainable management of water resources worldwide[1]. Yet, water stress[2] already affects 2.2 billion people around the world today[3], and numerous more species through polluted habitats and other biodiversity impacts[4]. Additionally, pressures on water resources and systems around the world are only increasing as demand is rising while both availability and quality are decreasing.

Total water demand is likely to keep increasing as a result of a growing population[5], and in certain parts of the world, also growing per capita consumption[6]. While not all of this consumption is needs-based, especially in richer countries, the Environmental Protection Agency (EPA) does estimate that climate change will cause and overall increase in society's water needs[7].

Potable water is finite, however, as is nature's ability to clean pollution. The most prominent polluters of water are agriculture, mining, and other industrial wastewater[8]. Among other harm, their activities significantly pollute and deplete water, exacerbating water scarcity and furthering the deterioration of ecosystems. Moreover, aging and outdated water infrastructure is causing the unnecessary waste of crucial water resources, impacting its quality, affordability, and availability. Ultimately, this affects things like biodiversity, increasing species migration and sensitization to habitat changes[9].

The inadequacies in our water systems also often reveal ongoing societal issues, as water scarcity and water stress disproportionately affect minorities and women and children, as well as low-income countries[10]. For example, in low-income countries it is often girls and women that spend much time collecting water, which they otherwise could be spending in educational tasks. There are also geopolitical implications from water scarcity, including the possibility of rising tensions between countries over water resources and large groups of migrants[11]. For example, the UN estimates that water scarcity could trigger massive migration of around 700 million people, displaced within the next five years[12].

It would be a mistake to think that water is only an issue for low-income countries. The United States (US) is the regional focus of this paper, and this country too has a relatively long history of water-related challenges. During the 19th century, the US faced its first water-related crisis: the need for water infrastructure that could transport water across cities. Rapid urbanization and industrialization necessitated larger quantities of water as local resources no longer sufficed for the growing population[13]. By the turn of the century, the US was facing a second water-related crisis, this time regarding wastewater treatment. As water use grew along with the population, so had the amount wastewater. Disease-ridden communities had become more common, and consequently, addressing waterborne illnesses became a priority. By the end of the century, this crisis had been resolved thanks to water filtration and chlorination.



Sunset over a water treatment facility.

1 United Nations (2024)
2) European Environment Agency. (n.d)
3) United Nations (n.d.)
4) Sabater et al (2018)
5) Office of the Director of National Intelligence (n.d.)
6) Ritchie & Roser (2024)
7) EPA (2024, July)
8) Denchak (2023)
9) Bagayas (2021)
10) United Nations Water (n.d.)
11) United Nations Water (2024, March)
12) UNICEF (n.d.)
13) Sedlak (2019)
14) Sedlak (2019)

After the second world war, the US faced a third water-related crisis as foul odors, dead fishes, and algal blooms pervaded national lakes, rivers, and waterways – one of many remnants of the war. In response, the EPA passed the first federal law regulating water pollution. The Clean Water Act (CWA) established requirements for water and sewage treatment, as well as maximum contamination levels (MCL) of different pollutants[14] .

Today, the US is facing its fourth water-related crisis, which interestingly, contains aspects of all the previous ones. Water availability is decreasing due to, among many reasons, inadequate water infrastructure, like in the first crisis. And although total water demand peaked around 1980 thanks to significant efficiency gains, a growing population is still putting additional stress on American water resources. More than half of the continental US has already regularly been experiencing drought conditions over the past two decades[15], and it is estimated that over the next 50 years almost half of US freshwater basins will be unable to meet their monthly water demands[16]. The issue of the third crisis, water quality, in some ways has worsened over time too, as more contaminants and many new toxic chemicals from industrial processes and other pollution kept being released into American waterways[17].

There are also relatively new developments adding to the current water crisis in the US, such as the effects from climate change. Overall rainfall is predicted to decline because of climate change, by as much as 25% in the West over the next decades[18]. At the same time, higher temperatures will increase evaporation and aridification. For example, one of the nations' largest water resource pools, the Colorado Basin, which supplies water to 40 million people has experienced historic drought conditions and lost around 10 trillion gallons of water already[19]. While partially due to the overextraction of water, experts claim this aridification has been significantly exacerbated by climate change[20].

As mentioned, the state of the US water infrastructure is a major threat to water sustainability in the country. More than 2.2 million Americans lack access to running water or have limited sanitation capabilities[21]. In 2021, the American Society of Civil Engineers (ASCE) gave the US' water infrastructure a C- grade and its wastewater infrastructure a D+ grade[22]. The ASCE noted that this grade reflects the physical infrastructure state, including leaky pipes and outdated treatment facilities, but also other threats like insufficient funding for repairs and upgrades, an aging workforce, and organizational fragmentation.

This note illustrates how water infrastructure interacts with the other mounting demographic and environmental pressures on water. There is the obvious added stress to availability from an aging infrastructure. Experts estimate that 700 to 800 main water pipe breaks every day, or approximately 292,000 per year [23]. About 16% of treated wastewater —7 billion gallons each day — is lost before it reaches its intended destination due to leakage. Outdated water infrastructure also poses direct risks on water quality, as the well-known case of lead-poising from corrosive pipes of the water supply in Flint, Michigan, exemplifies[24] . Lead is but one water contaminant, however. Many more water pollutants have reached the news recently, including per- and polyfluoroalkyl substances (PFAS) or so-called "forever chemicals", which can now be found in at least 45% of our water[25].

Stock photo of sample collection for microplastics testing.

14) Sedlak (2019)
15) The Nature Conservancy (2020, February)
16) Zee & Gewecke (2023)
17) Casale et al. (2022)
18) The Nature Conservancy (2020, February)
19) Mullane (2023)
20) Mullane (2023)
21) McGraw (2022)
22) American Society of Civil Engineers (2021)
23) American Society of Civil Engineers (2021)
24) Olson (2016). It should be noted that this case was marked by a confluence of factors, and not one single cause. The budget-motivated decision by government officials to change the city's water supply to the Flint River and avoid expenditures on pipe repairs as well as corrosion treatment was another major contributor.
25) Tap water study detects PFAS 'forever chemicals' across the US (2023)

Estimates for necessary main pipe repair and general water infrastructure investments amount to over $600 billion over the course of the next 20 years[26]. Besides aging infrastructure, an aging workforce — often referred to as the "Silver Tsunami" — is further contributing to a loss of expertise, which can be expected to add further challenges to proper management of our water systems.
Recently, there have been legislative efforts in response to these challenges of US freshwater water systems. The Bipartisan Infrastructure Law (BIL) in particular represents a historic investment in modernizing and improving water resiliency in the US, with a focus on replacing lead pipes, fixing leaks, upgrading treatment facilities, improving water quality, and enhancing the sustainability of American water resources.

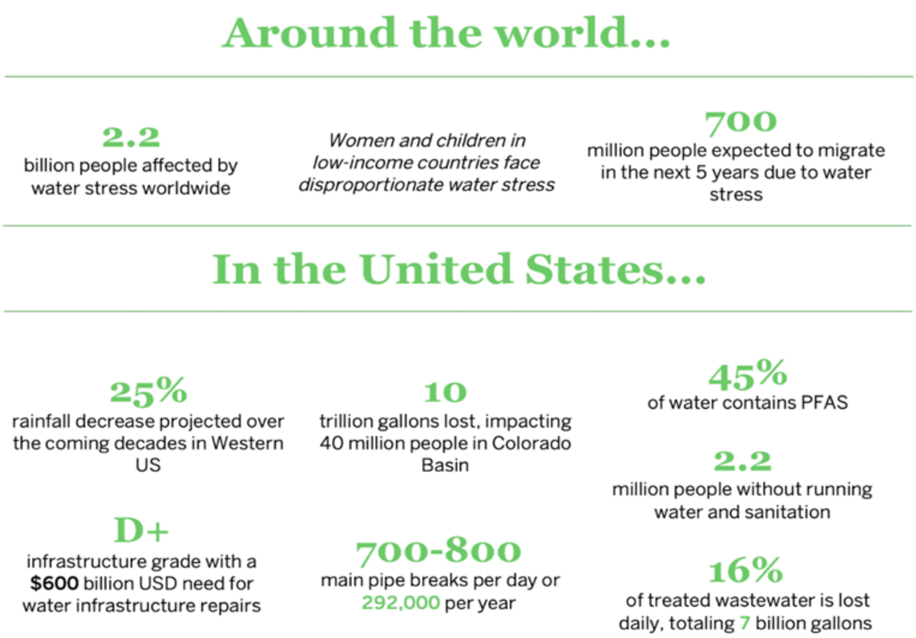
With this paper, Schneider Electric's Sustainability Research Institute aims to contribute to this important topic with its analysis on the US water infrastructure. A focus on infrastructure means that the agricultural sector, by far the biggest water user overall, receives comparatively little attention. This focus on infrastructure does not mean that causes of the American water crisis other than the physical state of infrastructure are ignored. On the contrary, the analysis will consist of identifying the many interacting environmental, technical, and social/regulatory aspects at play, and subsequently using this overview to describe opportunities for synergies.

In the following chapter, we start with the environmental lens, covering the water cycle and our interactions with it, water quality, and the health of aquatic ecosystems. Next, we will delve into the technical aspects, including the physical components of the US water infrastructure, wastewater treatment processes, operations, as well as the infrastructure's current state and major challenges. Finally, we will discuss the regulatory, economic, and governance aspects in the social lens: What affects US water infrastructure regulation? Who are the key players and their incentives? What does the public think, and why does that matter?

Each of the lenses concludes with a short section that considers a few broader systems, after which connections are depicted in a causal loop diagram (CLD). In these CLDs, all connections are directional. They typically are one-directional, except for a few which are bidirectional, as indicated with arrows on both ends. An arrow with a "-"sign means that an increase in the causal factor has a diminishing impact on the factor it points towards, i.e., a negative impact. An arrow with a "+"sign indicates a positive impact. Positive or negative do not indicate whether an impact is desirable or not. The feedback loop between carbon pollution, climate change, higher temperatures, and more energy use is a positive (or: reinforcing) one, for example, but is undesired.

The subsequent analysis in Chapter 3 starts with an overview of all the identified environmental, technical, and social interactions. It is followed by identification of areas of particular interest because of potential for synergistic action-taking by these key players, i.e., the reinforcing loops that are indeed desired. The second part of that chapter consists of concrete, promising, real-life examples of what such action-taking could look like. This report concludes with a brief summary, conclusions, and recommendations for further research on possible legislative initiatives, citizen projects, and business actions.

Exhibit 7. Key statistics on water infrastructure.



26) American Society of Civil Engineers (2021)

Chapter 2 Interconnections

Environmental lens

This first lens covers environmental factors, including the water cycle, aquatic ecosystems, and the relevant human aspects like health and the effects from human activity on the ecosystem and water quantity and quality. Water use trends in the US specifically are also covered, and a brief look at even bigger systems at the end of the chapter puts everything in perspective. The interactions will be depicted in a causal loop diagram (CLD) to round out the chapter with a visual overview.

The water cycle

The water cycle describes the movement of water within the broader Earth's systems through the atmosphere, surface water, and the ground, while changing states from gas, liquid, and solid. Three main types of water interact with each other in this cycle: freshwater, saline, and brackish water (a combination of fresh- and saline water). Saline water is comparatively abundant, with 96.5% of Earth's water in oceans, 0.9% in other saline sources, and only 2.5% as freshwater[27]. While these three types of water interact through various processes in the water cycle, this report will primarily focus on freshwater.

Most surface water is stored in the ocean, along with lakes, rivers, and streams which are typically freshwater sources referred to as "pools". Other stores of water include groundwater aquifers, or saturated geological units that store and transmit water through the cracks and pores of sediment and rocks. Water is also stored in soil permafrost, ice sheets, glaciers, snowpack, the atmosphere, and in ecosystems like wetlands. (Additionally, water can be stored in human-constructed artificial reservoirs and structures, such as water tanks, but this is not considered part of the natural water cycle.)

Besides storing water, the water cycle enables the movement of water between the atmosphere, surface, and ground by changing states – referred to as water fluxes. Fluxes that circulate water across these three spheres include processes of evaporation (liquid surface water turning into the gas state), transpiration (release of water vapor into the air from soil and plants), precipitation, snowmelt, runoff, streamflow, groundwater recharge, and groundwater discharge. The most basic water cycle process starts with evapotranspiration, which is evaporation and transpiration from pools, plants, and soil combined[28]. Once water condensates enough to form clouds, atmospheric pressure propels precipitation, e.g., rain and snow. These processes enable water to move between the three main earth spheres.

Processes that involve water moving across the surface of the earth occur through snowmelt, runoff, and streamflow. As ice sheets, glaciers, and snowpack melt, these surface fluxes re-enter streams, lakes, rivers, and the ocean, feeding surface and groundwater pools further downstream. Furthermore, water moves between the earth's surface and ground through groundwater recharge and discharge. Groundwater recharge fluxes feed water into aquifers while groundwater discharges feed water back into surface pools. Here, an additional and important function of the water cycle is its water filtration capability. As water permeates through soil and descends underground, it feeds the water table, enabling healthy soils to filter pollutants and thereby purifying the water[29].

Evaporation over Yellowstone Lake, Wyoming.

27) Water Science School (2019, October)
28) Water Science School (n.d.)
29) Pierzynski (2021)

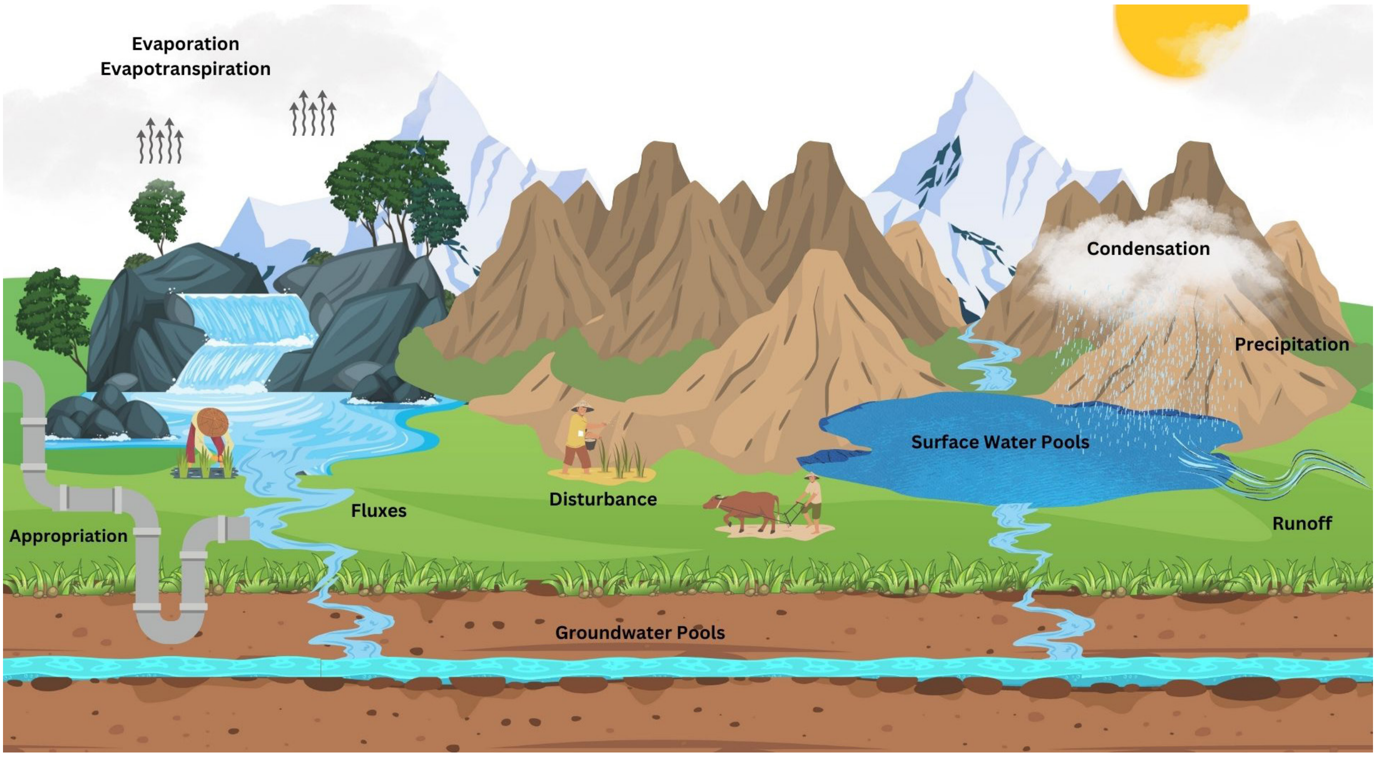
Importantly, the atmosphere, surface, and ground are connected through water. Altering the balance of any one of these spheres will affect other facets of the water cycle — and the overall ecosystem. They have a symbiotic relationship; however, current water management practices too often still treat them as separate. This has led to the mismanagement of surface water and groundwater resources. This brings us to human interactions with water cycle dynamics, which are significant enough that excluding them would render a conceptualization of water resources incomplete, even in the environmental lens. Such exclusions in the past have led to a deficient understanding of waters' temporal changes, perpetuating the issues of water overallocation and overreliance on human engineered water infrastructure[30].

Human interactions with the water cycle

Human impacts on water — and nature in general — can be restorative or harmful. On balance, the human impact on the water cycle in the industrial age has been a negative one, by temporarily or permanently degrading the functionality, resilience, and vitality of the three spheres.

Humans interact with the water cycle in three main ways, both directly and indirectly: by appropriating water resources (directly), by disturbing water resources (directly), and through climate change (indirectly)[31]. Appropriation of water resources refers to withdrawals (generally of freshwater) used for agricultural irrigation, drinking water, public supply etc. In this instance, water is directly extracted from its source and used for human purposes. Disturbances refer to activities that modify land cover, such as deforestation and the destruction of wetlands, which degrade the water and environmental landscape. This type of interaction depletes the source of water itself, and also tends to exacerbate climate change. For example, deforestation for agricultural expansion can deteriorate soil health, which diminishes not just its capacity for water storage and filtration, but also of carbon capture. It also degrades biodiversity by disturbing, if not destroying, native species' habitats and ecological balance. In fact, climate change and biodiversity loss have become major ecological threats, in general as they are both close to systemic tipping points[32], but also when it comes to water infrastructure.

Exhibit 8. The water cycle and human interactions.



30) Abbott et al. (2019)
31) Abbott et al. (2019)
32) Abbott et al. (2019)

Climate change interactions

To provide a clearer understanding of the interconnections between the water cycle and climate change, consider one of the most important drivers of climate change: our fossil fuel use. Extensive fossil fuel use contributes to significantly higher quantities of aerosols and greenhouse gases (GHG) in the atmosphere, causing atmospheric heating and more intense and frequent extreme weather events[33]. This is not simply because of overall higher temperatures, although of course that is an effect from climate change too. The accelerated evaporation and transpiration from pools, plants, and soil is changes precipitation patterns and deplete pools at quicker rates, which can increase the frequency, intensity, and distribution of rainfall[34]. Additionally, elevated atmospheric loads of sulfate, mineral dust, and aerosols, increase cloud cover and reduce solar irradiance, adding further warming effects[35]. This means, for instance, that storms are acerbated in wet regions, while drier zones experience a reduction in overall rainfall and worse droughts[36]. Climate change also impacts the soil's water retention capacity[37], and speeds up the melting of glaciers, snow, and ice caps, thus changing the timing and quantity of stream patterns[38]. In short, these climate-change induced effects interact with the water cycle by changing the water fluxes across the three spheres. Weather patterns are changed to where areas that are wet will become wetter and areas that are dry will become drier.

The latter consequence has obvious implications especially for arid states likes New Mexico, which is already categorized as extremely water stressed[39]. But even relatively wet states will face significantly bigger challenges in water management issues from more erratic and severe rainstorms.

Climate change also adds stress on water pools indirectly by its effects on human behavior. Overall higher temperatures as well as more frequent and intense extreme heat events mean that individuals use more water (to avoid dehydration), take longer and more frequent showers (to lower body temperature), and increase energy use (which take water to generate) for things like refrigeration and air conditioning[40]. The same is true for industrial operations, which might require more water to keep things cool. These form many reinforcing feedback loops between human activity, climate change, water stress, and human health – something we'll analyze more deeply in the Synergies Chapter.
Other consequences of the increased melting rate of glaciers, snow, and ice caps are sea-level rise, ocean acidification, wildlife habitat changes, and saltwater intrusion of freshwater resources[41]. In cities like San Francisco, the intensification of the water cycle due to warmer global temperatures has already been causing coastal erosion and lessened ecosystem resilience[42]. This brings us to the human impacts on (aquatic) ecosystems.

View of Golden Gate bridge and coastline in San Francisco.

33) National Geographic Society (2024)
34) Center for Science Education (n.d.)
35) EPA (2024, June)
36) Allan et al. (2020)
37) European Environment Agency (2019, September)
38) EPA (2024, June)
39) Hedge (n.d.)
40) European Environment Agency. (n.d.)
41) Center for Science Education (n.d.)
42) LeRoy Poff et al. (2002)

Aquatic ecosystem health

As briefly noted above, biodiversity loss and ecosystems damage are another (human-caused) environmental development accelerating our water challenges, especially concerning the health of aquatic habitats. The effects from climate change and human overuse and disturbance can induce "ecosystem distress syndrome", a by now prevalent occurrence(43). An ecosystem with this syndrome has reduced capacity to maintain vigor, organization, and resilience. Vigor represents the overall strength and productivity of an ecosystem. This includes an ecosystems' ability to sustain biological functions, support different forms of life, and maintain reproductive, evolutionary, and trophic energy processes. Organization refers to species diversity within an ecosystem and the number of interactions between them. A healthily organized ecosystem includes several distinct plant, microbe, and animal species that interact with each other through symbiotic relationships. Lastly, a resilient ecosystem remains stable when confronted with stressors, including anthropogenic disturbances. Distressed ecosystems, through lack of vigor, organization, and resilience, are less able to provide "ecosystem services", such as flora growth, water purification, and geographic stability. This also impacts humans directly through reduced production of food, clean drinking water, and protection from the elements.

A stressed aquatic ecosystem will suffer from biotic impoverishment (a reduction in diversity and abundance of different species), impaired productivity (inability to rapidly cycle nutrients, provide sources of sustenance for species, reduced energy flows), degraded water quality, water cycle disruptions, genetic favoritism for certain species, decreased resiliency to stressors, reduced ability to provide ecosystem services for economic purposes, and health threats to humans and other species(44).

A well-known example of an unhealthy aquatic ecosystem, which led to detrimental effects in society and the environment at large, is Cholera disease. Originally, this bacterial disease — which over time through repeated outbreaks has caused millions of deaths globally — was thought to spread only through infected humans. Today it is believed that contaminated drinking water is another major vector. Healthy aquatic ecosystems naturally foster bacterium environments, however, the combination of climate-induced warming, increased amounts of untreated waste and sewage in waterways, and heightened loads of agriculturally used nitrate and phosphorus, can significantly augment the proliferation of zooplankton and bacterium, severely magnifying the potential for development of bacterial diseases. The Cholera case exemplifies the strong link between healthy aquatic ecosystems and public health.

Water quality and pollution

Many industrial activities lead to the degradation of water quality, though things like nutrient loading, microbial contamination, acidification, sediment accumulation, and chemical pollution. Aggravating factors include climate change and inadequate water infrastructure due to age and improper management.

Nutrient loading, microbial contamination, acidification, sediment accumulation

One major form of water pollution today is nutrient loading, or excessive amount of nutrients in water, like nitrogen and phosphorus, which are often used as fertilizers in agriculture. These speed the process of eutrophication in water pools, or the de-oxygenation of water, fostering the growth of algal blooms and organic material which reduce water quality(45). One of many examples is the Salton Sea, also referred to as the "biggest environmental disaster in California history". A popular resort in the 1950's and 1960's, it is now completely abandoned after agricultural runoff caused mass die-offs of fish and other wildlife, still evidenced today in its beach consisting of fish bones.

Mummified Fish in Salton Sea, California

Microbial contamination is another way that water quality can become compromised. Pathogens from untreated sewage, livestock, and even the remnants of a wildfires, jeopardize the purity and can change the chemical composition of water, as the Cholera example illustrated.

Water is also degraded by acidification, i.e., a decrease in pH. This occurs through mining discharges(46), agricultural runoff (introducing ammonia into waterways)(47), and climate change. Acidification leads to acid rain, which impacts human health through respiratory diseases and potential lung damage(48) , and ecological health through the dissolution of nutrients like magnesium and calcium (necessary for forest health and biodiversity), among other things. The earlier-mentioned saltwater intrusion into freshwater resulting from climate change also causes acidification.

Furthermore, water quality can be affected through abnormal sediment accumulation. For instance, this occurs when rivers or lakes are dammed to create reservoirs. In such cases, sediment accumulates against the dam wall, settles at the bottom, diminishes streamflow, and decreases reservoir volume (taking up space that would otherwise be filled with water). This typically occurs because of improper dam infrastructure and/or management. Moreover, sedimentation may also occur because of land erosion, increasing the quantity of sediment transported in water, reducing streamflow, and inhibiting life in surrounding habitats.

43) Rapport et al. (1998)
44) Rapport et a. (1998)
45) The Editors of Encyclopedia Britannica (2024)
46) EPA (2023, December)
47) FoodPrint (2024)
48) EPA (n.d)

Chemical water pollution

Chemical contaminants from industrial and other activities, like heavy metals, plastics, pesticides, and pharmaceuticals are also often disposed in water pools, with the predictable result of damage to human and ecosystem health. Chemical bioaccumulation of these compounds in aquatic species may end up in humans when they consume seafood. But avoiding these chemical compounds is hardly as simple as avoiding seafood. Although the EPA has placed maximum contamination level (MCL) standards for many (but not all) chemical pollutants, these are nevertheless often still found in drinking water. An exhaustive list of harmful chemicals compounds is beyond the scope of this report, but some examples include arsenic, which is associated with skin, bladder, lung, kidney, breast, pancreas, and liver cancer in humans. Disinfection by-product contaminants also jeopardize water quality because of incompatible chemical interactions that can be carcinogenic[49]. Fracking-related substances are less common than some other compounds, but when they do seep into the water, its quality is significantly degraded through toxic, radioactive, and endocrine-disrupting chemicals. Then best-known examples of chemical compounds polluting drinking water are probably lead, and more recently, “forever chemicals”.

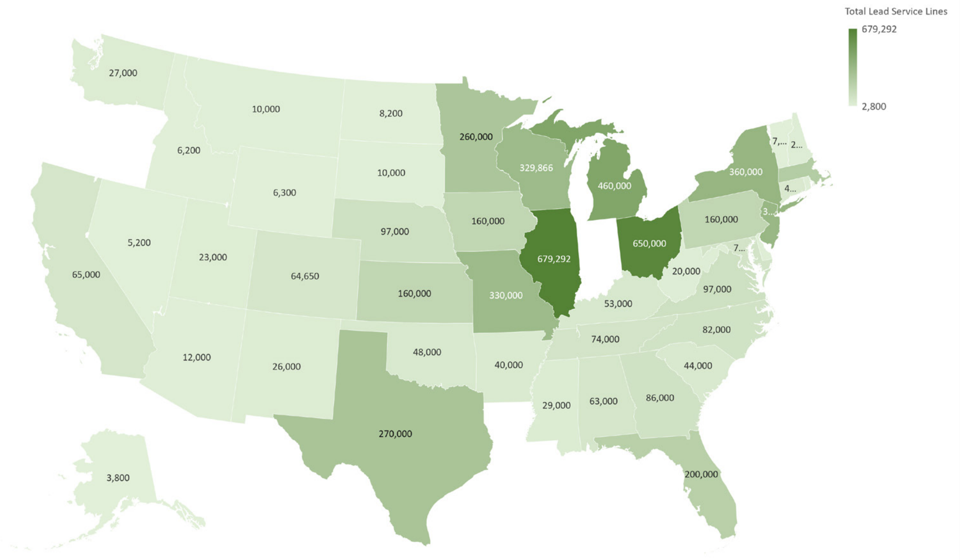
Lead is a carcinogen and thought to be related to immunological, renal, reproductive/developmental, nervous, and cardiovascular diseases[50]. Lead contamination usually occurs because of ineffective water conveyance, such as decaying and aging infrastructure that lends itself to seepage[51]. Climate change can also increase the conductivity and concentration of lead in water. Despite regulation banning their use for new construction dating back as far as 1986, water distribution systems in the US are still mostly comprised of lead pipes. Exhibit 9 shows the distribution of lead service lines across various states, illustrating the widespread presence across the country to this day. There have been many US cases of lead poisoning through drinking water over the years, the best-known is perhaps that of Flint, Michigan.

Box 1. Flint’s water crisis

In 2014, after switching the water source from Lake Huron to the Flint River, excessive lead levels were detected in Flint’s water supply, but the water was left untreated and used by the residents. Nearly 100,000 people by were exposed to harmful levels of lead, which sparked national outrage[52]. Lead is especially dangerous to minors, and the Hurley Medical Center found that a large portion of children and infants exposed to the city’s water had above-average levels of it in their bloodstream, significantly impairing their intelligence quotient (IQ) and brain development[53]. Some families reported having other adverse health effects like hair loss, skin lesions, chemically induced hypertension, loss of sight, and depression. While the effects of lead poisoning were becoming harder to ignore, officials continued to embellish the issue. This eventually led to a petition to end the city’s Flint River water supply which attracted 26,000 signatures, and a class-action federal lawsuit by the parents of affected children against the local government, Governor Rick Snyder, and 13 other public officials[54]. Ultimately, the Flint water crisis cost the US government $626 million[55].

City of Flint Water Plant.

Exhibit 9. Total lead service lines per State. Dataset from Olson & Stubblefield (2021).



49) Levin et al. (2024)
50) Levin et al. (2024)
51) Levin et al. (2024)
52) Lee et al. (2023)
53) Wang (2015)
54) Wang (2015)
55) Mills (2023)

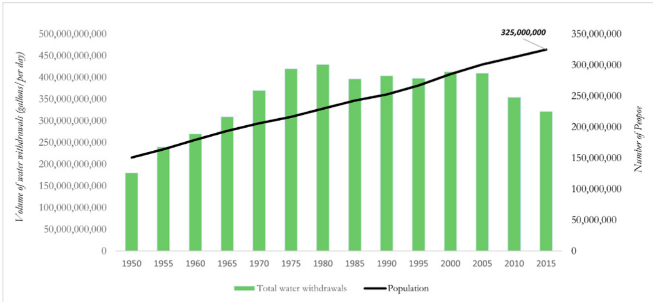
Another major contaminant that has recently attracted widespread public concern is a group of water pollutants referred to as per- and polyfluoroalkyl substances (PFAS). PFAS is a broad term encompassing an estimated of 14,700 different compounds — often called "forever chemicals." They are commonly found in our drinking water[(56)], although it should be noted the problem is wider spread than that; PFAS are practically everywhere, from our food to our clothing, cookware, cosmetics, packaging, and even hygiene products like toilet paper and shampoos[(57)]. It's estimated that around 98% of the US population has traceable levels of PFAS in their bloodstream[(58)]. The key danger of these chemical compounds is that they don't break down; hence the "forever" part. While residing and accumulating in the human body, over time and PFAS can start to cause serious health complications like immunotoxicity, dyslipidemia, changes in thyroid hormone levels, testicular/kidney cancer, and for those bearing children, changes in the newborn's birth weight. The recent spotlight on PFAS has led to regulatory action regarding their presence in drinking water[(59)]. However, the associated monitoring the treatment costs are sometimes prohibitively burdensome on Public Water Suppliers (PWS). For example, the Hyannis Water System in Barnstable, Massachusetts, recently adopted a PFAS treatment and monitoring system. This PWS supplies 14,000 people with drinking water, including underrepresented neighborhoods. They invested more than $20 million to install PFAS treatment technology in their groundwater wells. On top of this initial capital investment, they spend $800,000 in maintenance fees each year. General estimates conclude that for larger PWS facilities, the cost of installing and maintaining PFAS treatment and monitoring technology may exceed $1 billion dollars. Some PWS, especially those serving underrepresented and lower socio-economic status communities, may simply be unable to afford the necessary investments. For this reason, regulatory mandates on PFAS have not yet been broadly implemented[(60)].

In short, water quality is relevant for aquatic ecosystems, but also human health directly. Apart from impacting and relying on the quality of water, humans also demand much of water in quantity, with many implications for proper infrastructure needs.

Water use in the United States

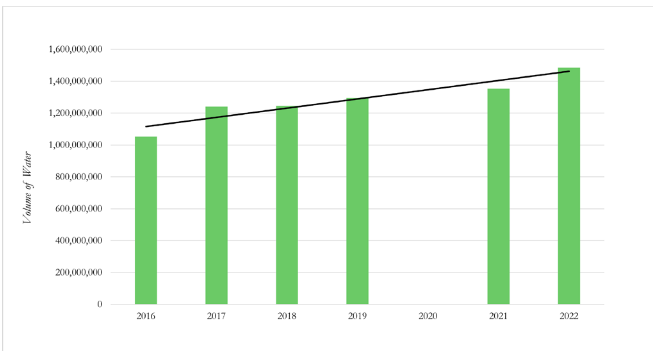
Around 322 billion gallons of water are used each day in the US[(61)]. Freshwater accounts for 87% of these withdrawals and saline water for 13%. Saline water can be made into drinking water through desalination, but this is an energy-intensive process, typically making freshwater the preferred option. Most US tap water comes from reservoirs, lakes, rivers, or water under the ground[(62)]. Public supply, agriculture, industrial activities, as well as thermoelectric power generation, draw predominantly on freshwater sources too. Over the past two decades or so, the annual US population growth rate was less than 1%[(63)] — and is predicted to fall in the upcoming years[(64)]. Water withdrawals peaked over four decades ago according to official data, and show what could be a decline over the more recent years[(65)].
However, the last datapoint in the official series is from 2015, so concluding this is a definite trend might be premature. Nonetheless, it can be said that water efficiencies have outpaced population growth and total water demand has not increased[(66)] .

Exhibit 10. US Population and water use over time. Dataset from Dieter et al (2018).



Nevertheless, experts believe there are still significant barriers to true water sustainability in the US[(67)]. For one, the current water consumption, while not increasing, is unsustainably high. The US per capita water footprint is 1,802 gallons per day[(68)] — larger than any other country's per capita water footprint, according to The World Counts[(69)]. Additionally, the pressures on clean water availability discussed are still increasing[(70)]. More people means also more demand for housing, food, and other products that require water and haven't necessarily shown the same gains in efficiency as direct water use has. Agricultural and industrial expansion, necessary to sustain the livelihoods of more people, will drive more natural destruction, create pollution, and exacerbate climate change, completing yet another undesired reinforcing feedback loop between climate change, water pools, and human activity. A national figure also obscures vast geographical differences; new construction in places with already strained water resources, for example, will further exacerbate water stress [(71)]. Indeed, the majority of new home markets are water stressed [(72)]. These points are encompassed in the fact that US water imports are still growing, see Exhibit 11[(73)]. The US ranked the largest importer of water worldwide in 2022[(74)], importing approximately 1.48 billion liters of water[(75)] — 9% more than in the previous year.

Exhibit 11. Volume of water imported into the US annnually. Dataset from Ridder (2023), Statista.



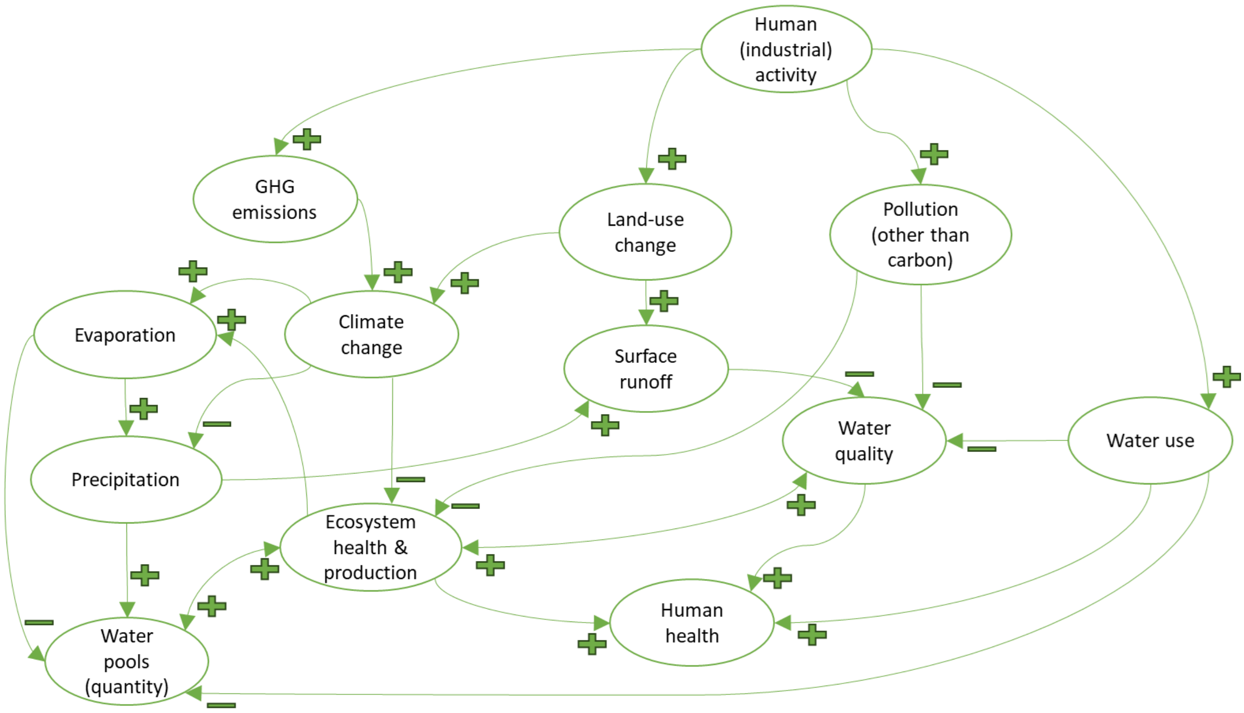
56) Tokranov et al. (2024)
57) Kluger (2023)
58) Levin et al. (2024)
59) EPA (2024a)
60) Levin et al. (2024)
61) Water Science School (2018)
62) U.S. Department of Health & 63) Our World in Data (2024)
64) Heggie (2020)
65) Warziniack et al (2022
66) Gleick (2023)
67) Gleick (2023)
68) Office of Sustainability (2022)
69) The World Counts (n.d.)
70) Gleick (2023)
71) U.S. Government Accountability Office (2014)
72) Meres (2024)
73) There is no data for 2020, most likely because of the chaos on international trade and global shutdown because of the COVID pandemic that year. It is possible water imports decreased that year, however, given that these were exceptional circumstances, we could consider that datapoint an anomaly even if it was not missing from databases.
74) Observatory of Economic Complexity (n.d.)

Connecting

The prime broader systems that should be kept in mind in this lens are the overall incredibly complex Earth systems that the water cycle is part of. Little has been said about the role of the ocean, for example, even though it's most of the water on earth and a bigger carbon sink than trees[76]. While we cannot label these systems irrelevant, going into these complex topics in any detail is beyond this paper's scope. This first Connecting section is short for that reason; the ones in the technical and social lenses will be more substantial. Below is the CLD for interconnecting environmental aspects on water, including those driven by human behavior (Exhibit 12). As mentioned before, an arrow with a "+"sign indicates a reinforcing (positive) impact, while an arrow with a "-"sign indicates a diminishing (negative) impact.

With this brief overview of the various environmental aspects of the water cycle and their interactions with human health and impacts, we'll turn to the technical lens, which contains a description of the physical and technological parts of US water infrastructure.

Exhibit 12. Causal Loop Diagram (CLD) of environmental interactions.



76) E.g., United Nations (2023)

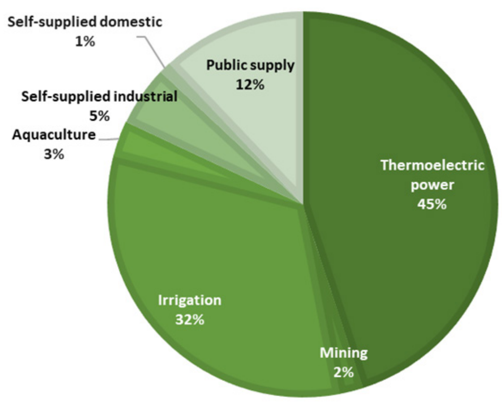
Technical lens

Physical water infrastructure refers to things like dams, pipes, pumps, storage and water treatment facilities, and wastewater treatment plants. Technological components include monitoring tools and equipment such as sensors, meters, operational software, and digital infrastructure. Together, they form what is typically referred to as a water system: the infrastructure through which the water flows, as well as the chemical and automation processes that prompt this flow. These infrastructure parts and processes can vary based on whether the water utility, i.e., the organization managing the water system, is a municipality (public) or industry (private). That's why details and major challenges for municipalities and industry are discussed in two separate sections, after a general outline of the US water infrastructure landscape and the overarching challenge of its outdated state.

General US water infrastructure landscape

Every day, Americans use about 280 billion gallons of freshwater for various industrial and domestic purposes (Exhibit 13)[77] . This water is sourced and then distributed through a dispersed collection of independent private or public systems[78]. The entities responsible for the sourcing and transportation of the water are called suppliers. Sometimes, when necessary, the water is further distributed in the water network though utilities, who are responsible for transportation of water to end-point consumers. It's not uncommon to see water utilities and suppliers being conflated or used interchangeably in literature, because commonly they are the same entity.

Exhibit 13. Breakdown of uses for US freshwater withdrawals.



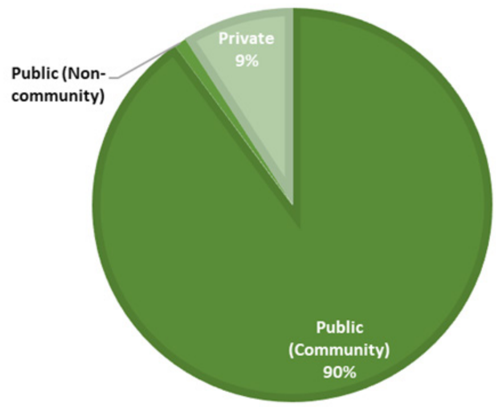
Water systems, suppliers, and utilities

At the highest level, there are private water systems and public water systems. This differentiation is based on the number of customers and connections they serve. Public water systems can be further divided into community or non-community systems, based on the kind of customers. Community public water systems deliver the vast majority of water to the US population, mostly but not exclusively through municipalities[79].

Community Water Systems (CWS) are used to supply water to the same population throughout the year and serve at least 25 permanent structures — and possibly a lot more[80]. Across the entire nation, there are approximately 160,000 independent water utilities, of which 52,000 are community-based[81,82]. The other 108,000 non-community water systems (NCWS) are further subdivided based on temporality, into transient or non-transient systems. Transient non-community water systems (TNCWS) provide water to 25+ customers for at least two months per year, or 60 days, but not on a permanent basis. Customers can include seasonal gas stations or campgrounds. Non-transient non-community water systems (NTNCWS) supply water on a regular basis to at least 25 permanent customers, such as hospitals, factories, office buildings, and schools, for at least half the year[83] .

Private water systems serve no more than 25 people, or 15 connections, at least 60 days of the year. Private water systems are owned by private entities, and retrieve water from non-public water sources, including springs, ponds, and residential cisterns or wells[84]. They can be as small as a private water well supplying one single residence, but also include larger systems such as for a business (up to 25 people)[85]. In the latter case, such a business by itself may be for-profit, but it should be noted that most private water systems are not for-profits; 22% operate on a for-profit basis, while the rest operate as not-for-profit systems. Examples of these include water cooperatives, or ancillary systems attached to an entity, like a business, whose primary function is not drinking water supply[86].

Exhibit 14. Share of water sales private versus public (community and non-community).



Suppliers and utilities are key stakeholders in US water infrastructure. Typical public water utilities are counties or special districts. Private water suppliers include privately-owned companies, businesses, homeowner associations, cooperatives, or individual property owners. Although the CWSs count the least entities, they are typically larger, much larger in some cases; 9% of CWS provide water for almost 90% of the US population, or around 300 million people, with the remaining CWSs supplying water to communities with under 10,000 people[87].

77) EPA (2024b)
78) McBride & Breman (2024)
79) Beecher & Kalmbach (2023)
80) EPA (2021)
81) ASCE (2021)
82) McBride & Breman (2024)
83) EPA (2021)
84) EPA (2023, February); EPA (2017a)
85) EPA (2023, February)
86) Beecher & Kalmbach (2023)
87) McBride & Breman (2024)

Exhibit 15. Overview of the kinds of water systems in the United States.

	Public (25+ customers)			Private (< 25 customers)
	Community	Non-Community		
Water use share	90%	1%		9%
		Transient	Non-transient	
Number	52,000	Up to 18,000	85,000	150,000 – 160,000
Kinds of customers	Residences, permanent businesses.	Some gas stations, campgrounds.	Factories, office buildings, churches, schools.	Single residences or a small group or business.
Kinds of suppliers	Counties, special districts, or rural cooperatives.			Businesses, homeowner associations, or individual owners.

The CWSs often have more stringent regulatory enforcements and oversight, particularly regarding compliance with water quality standards. On the other hand, while regulation exists for non-community public and private water systems, it is often difficult to enforce due to their small scale, variety, sometimes transient nature, and private ownership, which among other things, often translates to inadequate bookkeeping and a lack of unform standards to test compliance to[88]. Despite their small individual sizes, private water systems collectively are not insignificant, reaching roughly the same count of systems as the public ones. As mentioned, they are much smaller in market share (as measured by water sales). Because TNCWS and NTNCWS are by far the smallest stakeholders, they will not be the focus in this document.

Treatment facilities

The US water infrastructure also includes treatment facilities of water (before use) and wastewater (water after it has been used for domestic, commercial, and industrial purposes). Treating wastewater is essential for maintaining water quality and the health of aquatic ecosystems, as most treated wastewater is released back into the environment and current-day water pollution is more than most ecosystems' absorption capacity[89]. Treatment facilities could be considered a human attempt to augment the water cycle with technology.

Across the country, there are approximately 16,000 public treatment plants[90]. These facilities, known as Publicly Owned Treatment Works (POTW), are responsible for storing, treating, and recycling (waste)water. POTW treat water and wastewater coming from municipalities, special districts, or other publicly owned entities. The process is complex, as well as expensive because of the energy required to manage the residues, known as "sludge". Every year POTW generate around 13.8 million US short tons of sludge, which is one of the most energy-intensive materials to treat, accounting for 33% of the total energy used in wastewater treatment[91].

In addition to POTW, there are stormwater utilities and privately-owned facilities, but these do not disclose many public figures about how much water is treated. Stormwater utilities operate in over 40 states. These entities treat water affected by storm sewers, roadside ditches, and flood control reservoirs[92]. Then there is industrial wastewater, which is typically treated by privately-owned facilities. Industrial and commercial discharge is bounded to certain limits and conditions through the National Pollutant Discharge Elimination System (NPDES) program, which are largely determined by standards for the type of activity or facility producing the wastewater[93].

Pipes and dams

There are 2.2 million miles of underground pipes across the US, primarily owned by public utilities, distributing around 39 billion gallons around the country per day[94]. The exact number of privately owned pipes is not readily available.

The US counts approximately 91,886 dams, with an average age of 63 years[95]. Dams provide many benefits like spaces for recreation, support for transportation infrastructure, and most important for the topic in this report, serve as water supply pools. It should be noted however, that they also come with significant drawbacks for water and general sustainability. Dams disrupt the natural flow of water, damaging fish's migratory patterns, nutrient recycling, soil erosion, salinization, and waterlogging. They also are responsible for 1.3% of global GHG emissions due to forest clearing and methane released by microbial environments that form in the sediment accumulating in the riverbed[96]. For water sustainability specifically, the most concerning issue is that holding water in these large dam reservoirs accelerates evaporation rates, because non-fluxing water warms quicker. This phenomenon accounts for the loss of 170 cubic kilometers of water annually, or 7% of total freshwater consumed by humans[97].

More than 56.4% of all US dams are privately owned — a number that, contrary to the situation for underground pipes, can be determined because privately-owned dams can be counted from outside observation — with the remaining ones either state, locally, or federally owned[98].

88) Beecher & Kalmbach (2023)
89) Center for Sustainable Systems (2023a)
90) McBride & Breman (2024)
91) Center for Sustainable Systems (2023a)
92) ASCE (2021)
93) EPA (2024, September)
94) ASCE (2021)
95) National Inventory of Dams (2020)
96) Baroud (2023, July)
97) Baroud (2023, July)
98) National Inventory of Dams (2020)

Hoover Dam, Nevada and Arizona.

Federally owned dams are overseen by the U.S. Army Corps of Engineers (USACE) and the Bureau of Reclamation. As with pipes, the decentralized nature of dam management poses issues for maintenance. This is particularly relevant to perhaps the biggest crisis of US water infrastructure, outdatedness, which will be described in depth in the last section of this chapter. For now, with the above general foundation, we turn our attention to municipal water infrastructure, with an in-depth look at the unique structure and operations of the local systems that directly serve communities.

Municipal water infrastructure

Municipal water in the US serves a diverse array of users and includes not just households and public facilities, but also businesses, agriculture, and some industry sectors[(99)]. Water utilities typically withdraw water from either surface- or groundwater sources, with surface-water retrievals superseding those of groundwater (237,000 versus 84,700 million gallons per day)[(100)]. These withdrawals are then distributed for, among other things, domestic use, public supply, and industrial activities such as thermoelectric power generation, irrigation, livestock, and aquaculture, through the water distribution network.

Water supply systems and water treatment

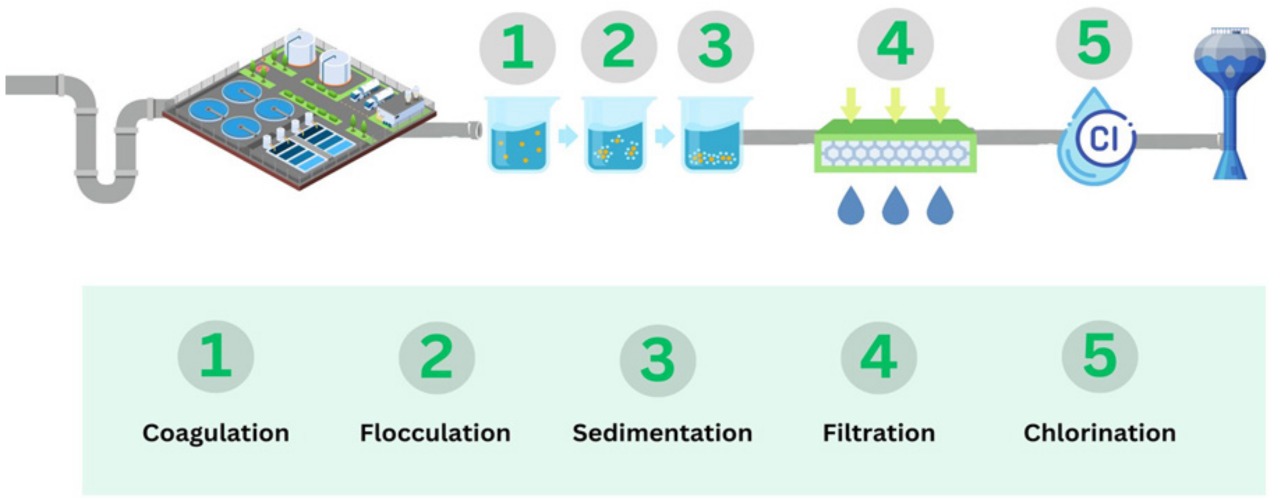
Water distribution networks consist of interconnected components including pipes, pumps, valves, treatment plants, and storage facilities[(101)]. Depending on the end-use of water, a treatment plant may be absent in the network; this is the case when the water quality from specific sources is up to par with regulatory standards. Starting at the water source, a combination of mechanical and engineering processes draws up water with pumps, intake structures (for surface-water), wells (for groundwater), or canals and pipelines (where water is directly channeled to treatment facilities). The extracted water is then sent through underground pumps to a water treatment plant, if necessary, where it undergoes chemical and physical treatment until it meets water quality standards. Subsequently, the treated water is transported via underground pipes to a community water utility, where it is stored in a storage tank before being distributed to the end-users (households, businesses, fire department, etc.).

The water treatment involves a series of steps. The first step is called coagulation, in which positively charged chemicals (such as salt, aluminum, and iron) are added to the water to counteract the negative charge of dirt and other particles[(102)]. Step 2 is flocculation, where the water is mixed until the fine particulates in the water form heavier particle conglomerates, or “flocs”. In step 3, the flocs are allowed to sink to the bottom of the water, where they separate into solids (at the bottom of the tank) and liquids (water) during what is called sedimentation.

The next and fourth step is filtration: clear water sitting atop sedimented flocs is sifted through with filters. These filters have various pore sizes, depending on the material composition (for example sand, gravel, or charcoal) and remove bacteria, dust, viruses, chemicals, germs, and parasites from the water. At this point, more advanced water treatment facilities may choose to treat water through ultrafiltration, where water is forced through an ultra-thin membrane to remove smaller particles. Another technique worth a very brief mention is reverse osmosis, which removes ions, molecules, and larger particles using a semi-permeable membrane. This technique is often applied to recycled or saline water.

99) Center for Sustainable Systems (2023b)
100) Water Science School (2018)
101) EPA (2023, July)
102) U.S. Department of Health & Human Services (2022, May)

Exhibit 16. Water treatment process.



The fifth and final step in the treatment process is disinfection. Additional chemical disinfectants like chlorine, chloramine, or chlorine dioxide, are added to the water, with the purpose of removing any remaining pathogens the water comes in contact with inside the underground pipes or storage tanks throughout the distribution process[103]. Unless the chlorine has been overused, it should have dissolved and be mostly or completely removed by the time the water reaches its destination. (If you as a residential user want to make sure: leave the water exposed to the air for a little bit after pouring it from the tap. Chlorine is a volatile compound and will evaporate naturally.) Although chlorination is the standard practice, modernized water treatment facilities often use ultraviolet (UV) light for disinfection purposes. It should be noted that while UV light exposure has the same effectiveness as chlorination in terms of killing pathogens, it does not have effects beyond exposure. In other words, UV light can substitute for chlorination in the final disinfection step of the treatment process but does not ensure the quality of treated water as it travels through the water distribution system – something to keep in mind if one has reason to expect parts of the distribution system may be of low quality.

Wastewater Treatment

After water has been used by households, businesses, or industries, its quality has often been severely reduced. Usage in sinks, toilets, laundry machines, showers, and dishwashers will have introduced new chemical compounds, dirt, and other particles to the water. Industrial, agricultural, or other business activities may introduce remnants of metals, plastics, pesticides, fertilizers, and many other chemical contaminants that affects waters' purity. Releasing it directly back into waterways would cause harm to wildlife, ecosystems, recreational options, and human health, from the effects mentioned in the environmental lens (i.e., eutrophication, microbial contamination, acidification, sediment accumulation, and chemical pollution)[104]. Therefore, once it exits the household or business compound, what is now called wastewater is transported through underground pipes to a Publicly Owned Treatment Work (POTW) facility.

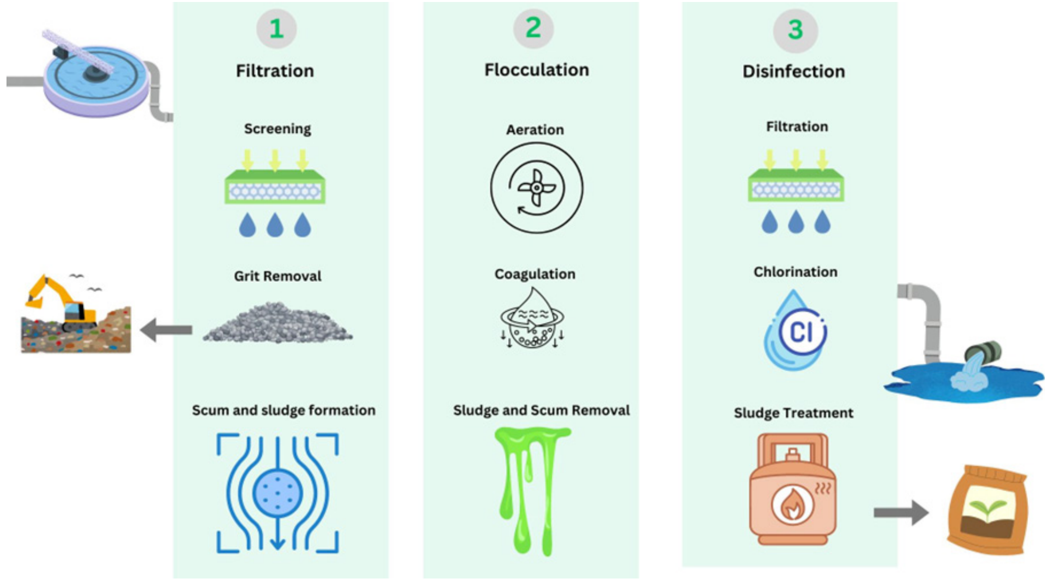
The wastewater treatment process can be divided into three main stages: primary, secondary, and tertiary treatment[105] . There is more variation in wastewater quality and therefore treatment compared to water, which is why it will be described in more generic "phases" rather than steps. In each consecutive stage, smaller materials are removed from the water, sometimes with steps that the reader will recognize from the water treatment process. As during water treatment, the material that settles at the bottom of a tank throughout the wastewater treatment process is called "sludge". Additionally, the heaviest materials are referred to as "grit". Lighter materials will float to the top, forming what is called "scum".

In the primary phase, also referred to as sedimentation or filtration, solids are removed via a screening process. Wastewater is scanned through a coarse debris screen for things like wood, rocks, and other solid organic matter. If found, these items are extracted and sent to landfills. Wastewater is held in tanks in this phase, also leading to sludge and scum formation.

In the second phase, also called flocculation, organic matter is treated and removed. Wastewater is shaken and aerated (exposed to air), which releases dissolved gases. This process is aided by coagulation, i.e., adding substances to the water which cause organic particles in the water to lump together in flocs. Wastewater is then transferred to another tank, where pumped air oxygenizes it, causing smaller organic material (e.g., sand or coffee grounds) to suspend and form grit and / or sludge at the bottom of the tank. Once the grit is settled, it's taken out and sent elsewhere, typically to landfills. The sludge is separated from the wastewater and stored elsewhere in the facility. Scum – consisting of things like grease, oils, plastics, and soaps in a layer at the top of the water– is also removed and subsequently thickened. The thickened scum is subsequently deposited into a digestor tank together with the sedimented sludge.

103) U.S. Department of Health & Human Services (2022, May)
104) Water Science School (2018a)
105) Water Science School (2018a)

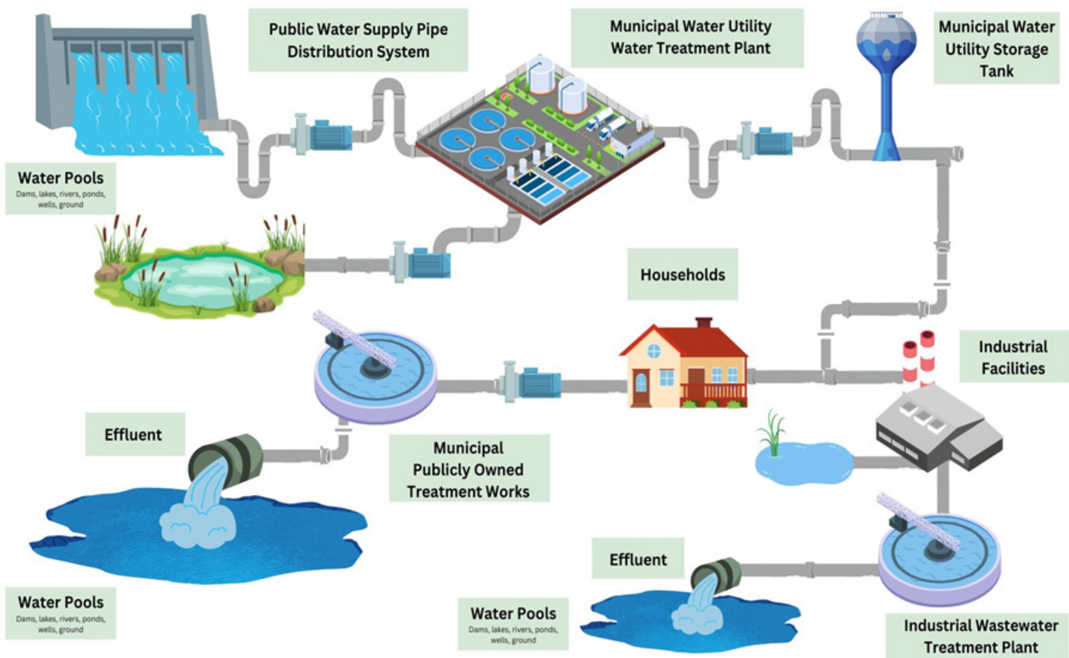
Exhibit 17. Wastewater treatment process.



In the last phase, also called polishing, the water is disinfected. Sometimes the wastewater is filtered through a sandy or charcoal surface beforehand, which removes bacteria, odors, and any small particles that may cause some remaining turbidity. The wastewater is transferred into a new tank where chlorine is applied. As in water treatment, chlorine kills bacteria and offsets other chemicals. At this stage, the water is called “effluent”, or treated wastewater, which is usually safe to release into the environment. The wastewater-derived solids that resulted from thetreatment (i.e., the sludge and thickened scum) are kept in storage for 20-30 days within digestor tanks. Digestor tanks are closed, heated tanks, which digests solids through bacteria, ultimately diminishing the volume, smell, and any organisms in the solids (which otherwise pose disease risks). The final result is used as fertilizer or sent to landfills[106].

Once released back into the environment, the water cycle as done by humans starts anew, with water taken from water pools for treatment and subsequent distribution thought the distribution network. This complete cycle is depicted in Exhibit 18. Industrial facilities are mentioned in this as well, and a detailed description of water treatment specifics for this sector is provided in the following section.

Exhibit 18. General cycle of US water supply systems.



106) Water Science School (2018b)

Industrial Water Infrastructure

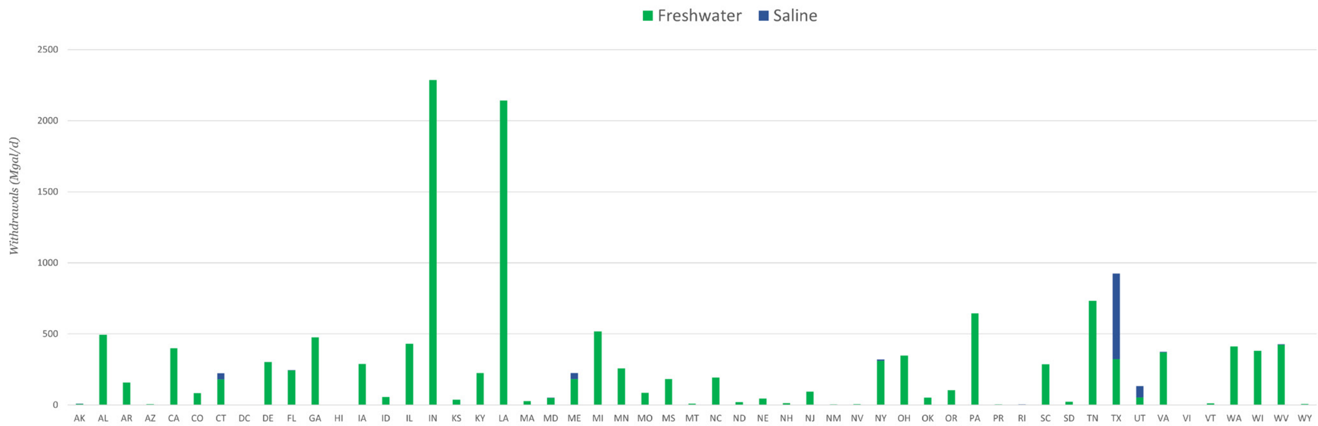
While municipal water systems are crucial for ensuring safe and potable water for public consumption, industrial water processes play an important role in manufacturing and production activities, each with their own set of challenges and requirements. The ways that water is utilized, processed, and treated vary significantly between municipal and industry spaces, and even within industries themselves. What follows about industrial water use and treatment is a general description.

Water use and treatment

The first major difference is the way the water is used; while municipal water systems aim to provide water for residential, commercial, and public use, industrial water is typically used for cooling, heating, manufacturing, and sanitation. Secondly, quality requirements vary significantly. In the municipal space, water quality standards are for the most part universal, i.e., uniformly potable. For industry uses, the standards vary by sector, activity, and the type of pollutants water is exposed to. Industrial water and wastewater treatment processes vary accordingly, whereas municipal water systems use a more consistent approach to treat water and wastewater (as outlined in the previous section). Finally, while municipal water systems can be distributed over a wide area, serving entire cities, communities, or districts, industrial water is often localized, serving only the industrial facility itself.

Self-supplied industrial water withdrawals are estimated to be more than 18,200 million gallons per day, which constitutes about 5% of total US water withdrawals, mostly from surface water sources (82%)[107].

Exhibit 19. Self-supplied industrial withdrawals. Note that non-self-supplied withdrawals, such as public supply withdrawals used for industrial purposes, are not depicted in the graph. Dataset from Dieter et al. (2018).



While municipal and industrial water provisions are usually separate in the physical sense, municipal water systems provide an additional 39,000 million gallons a day for industrial use[108]. In other words, the majority of total water used in industry still comes from the public water system, with withdrawals amounting to around 12% of daily total public supply and more than double the self-supplied amount. This brings the estimated total of industry water use to roughly 58 billion gallons a day.
Some relatively major water users include the sectors energy and chemicals, manufacturing, food & beverage, and primary mining, metals, and minerals industries (MMM). Within manufacturing, semiconductors and papers are relatively water-hungry, although their total water footprint is smaller than other sectors because of those sectors' smaller market size. Exhibit 20 shows each of these sectors' absolute water use, its share of total industrial water use, share in the US economy for comparisons (measured by GDP,) and main uses within that sector[109]. (Please note that the below rows are not to be added; the table does not cover all sectors, and paper and semiconductors are part of manufacturing sector.)

Exhibit 20. Water use and purpose of industry segments.

Sector	Water use (Milion galllons/day)	Share of industrial water use	Share of GDP	Uses
Energy & chemicals	26,400	45.5%	25%	Cooling
Manufacturing	18,200	31.4%	11.4%	Cooling, cleaning, conveying, and embedding in products
Food & beverage	4,800	8.3%	5.6%	Cleaning, as ingredient, cooking
MMM	4,000	6.9%	1.4%	Liquid/metal extraction, dust control, quarrying, milling
Paper and paperboard	4,000		0.5%	Cooling, cleaning, conveying, and embedding in products
Semiconductors	723		0.3%	Cooling, cleaning, conveying, and embedding in products

107) EPA (2024c)
108) United States Geological Survey (2023a)
109) Erickson (2023) ; Ellis et al. (2009) ; Dieter et al. (2018); Meninger (2024); U.S. Department of Energy (2024); U.S. Department of Agriculture (2024); U.S. Bureau of Labor Statistics (2024); Thadani & Allen (2023)

There are three main categories of water use across most industry sectors: cooling, process, and boiler feed[110]. Broadly speaking, cooling water dominates across the chemical and energy sector, process water in the manufacturing and food & beverage sectors, while boiler feedwater dominates in the primary metals and mining sectors.

Cooling water systems

Cooling water systems are used to dissipate the heat that's generated during industrial processes, machinery operation, or power generation[111]. These various cooling processes, which together form the biggest water use category within industrial sectors, include refrigeration, air conditioning, and in some sectors, the cooling of molten metal. Cooling needs naturally vary between industries, but for good measure: it's not uncommon for one single cooling water system to require 1 gallon per minute, resulting in a typical annual use of around 525,000 gallons of water[112]. There are three main types of cooling methods: once-through cooling, open-recirculating cooling, and closed-recirculating cooling. Once-through cooling systems use water from nearby sources and circulate it once through the system before discharging back into the water source. Open-recirculating cooling systems recycle some water, while close-recirculating cooling systems continuously recycles it. All these methods take considerable amounts of water, but as the reader might have guessed, closed-recirculating cooling systems are the least water exhaustive. On the other hand, once-through cooling systems are significantly more exhaustive and, because of the amount of water charged back into water sources, have been known to severely impact environmental health. Open-recirculating cooling systems fare better, but still use significant amounts of water. After use, cooling water is degraded in quality through chemical and organic contaminations. Because of its elevated temperature, it could also cause severe thermal pollution if it were to be discharged without proper wastewater treatment.

Process water

Process water is the category for the myriad of ways water is used within industrial processes. In the food & beverage industry, for example, process water is used as an ingredient, for temperature control, and to wash, rinse, or sanitize products[113]. In the petroleum and refining sector, process water is often used for catalyst regeneration and to wash products. In facilities across sectors, process water may be used for vehicle and equipment cleaning. As can be imagined, water quality is degraded after these processes, severely in some cases.

Boiler feedwater

Boiler feedwater processes involve heating water for steam generation, where energy is subsequently captured and utilized for different operations as a power source. Additional water is necessary to replace the water lost during the process, which is called makeup water[114] . Water quality is also typically degraded during the process, as boiler feedwater systems frequently encounters issues such as corrosion, scaling, and fouling. Corrosion deteriorates water quality by leaching harmful metals into the water, while scaling increases the mineral content in water leading to what is commonly referred to as hard water. Similarly, fouling can lead to microbial growth and other effects that diminishing water quality.

Water being discharged into a river.

110) Meese et al. (2022)
111) Meese et al. (2022)
112) EPA (2017, November)
113) Moreno (2024)
114) Meese et al. (2022)

Wastewater treatment & water reuse / recycling

Industrial wastewater treatment processes vary significantly depending on kinds and extent of water quality degradation, but there are a series of generic steps that almost all industry sectors follow. All methods as discussed in municipal wastewater treatment, including filtration/sedimentation, flocculation, and disinfection methods are typically also used in industry wastewater treatment. There may be additional treatment after that, depending on the type of wastewater. For example, if the water is heavily laced with sulfates, lime or lime soda may be used to balance pH levels[115]. If the resulting solution contains heavy metals, additional steps are taken to remove these.

There are two main types of wastewater treatment, used on a case-to-case basis: biological and physical-chemical processes[116]. Biological processes use bacteria to decompose organic matter in wastewater. On the other hand, physical-chemical processes involve some form of filtration and some form of chemical neutralizers. These processes can be used in conjunction, as it is the case in the food and beverage industry where biological treatment is used to process high organic loads and subsequent chemical treatments are used to remove any remaining contaminants in water, most commonly lipids.

At the end of the wastewater treatment cycle, the effluent is either distributed back into the facility for reuse or discharged in the environment or local sewer (in which most cases it enters the publicly managed water cycle)[117]. This might raise the question as to what extent the treated wastewater has been restored to its original quality. When this is not the case, it can lead to degraded ecosystems, disruption of aquatic life, and disturbances to natural ecological processes, while also posing threats to human health due to the presence of toxic substances. Elevated levels of biological oxygen demand (BOD) and chemical oxygen demand (COD) reduce the oxygen content in water, causing suffocation in aquatic species. In addition to these environmental and public health risks, inefficient wastewater treatment can result in non-compliance with regulations such as the CWA, NPDES, SDWA, and state and sector specific regulations. This non-compliance may lead to significant legal fines and other repercussions for industrial facilities. Indeed, a major challenge for industrial water infrastructure specifically, is in fact meeting wastewater quality standards, as will be discussed among the other challenges to water infrastructure, in the next section.

Major challenges in the US Water Infrastructure

US water infrastructure is facing several major challenges today, threatening and to some point already affecting the reliability and efficiency of water systems. Water system failures, either continuous or sudden in nature, can result in more intense and frequent disruption of water services, significant water losses, imminent danger to community safety (such as through dam breaks), national security breaches (such as from cyber-attacks), economic damages and financial costs, and contaminations threatening both the health of ecosystems and humans[118]. The first one has already been mentioned: outdatedness.

Main pipe break.

115) SAMCO (n.d.)
116) Danau (n.d.)
117) SAMCO (n.d.)
118) Copeland (2010)

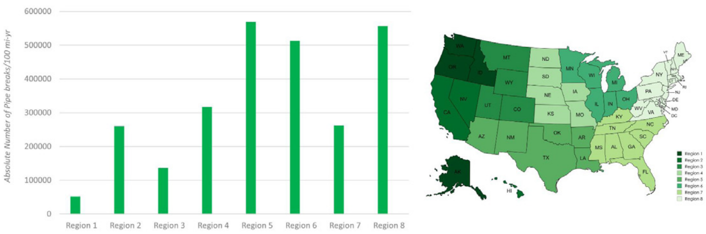
Outdatedness

The physical parts of the American water distribution networks are widely considered to have reached their age threshold, and beyond. The average operational lifespan of pipes falls within the 75–100-year span, while a large part of the US water infrastructure was established more than 100 years ago[119].

Aging pipes

Predictably, this aging has increased US water systems' vulnerability. As far back as 2002, the EPA was estimating that if the 600,000 miles of existing sewer systems were not updated in the coming years, the share of the network made up of deteriorated pipes was expected to rise to 44% by 2020 [120]. Between 2012 to 2018 there were 27% more main pipe breaks compared to previous years. Exhibit 21 depicts the absolute annual number of public pipes breaks per US region today.

Exhibit 21. Absolute number of pipe breaks per US region. Data is weighted and scaled to arrive at nationwide figures. Dataset from Barfuss (2023).



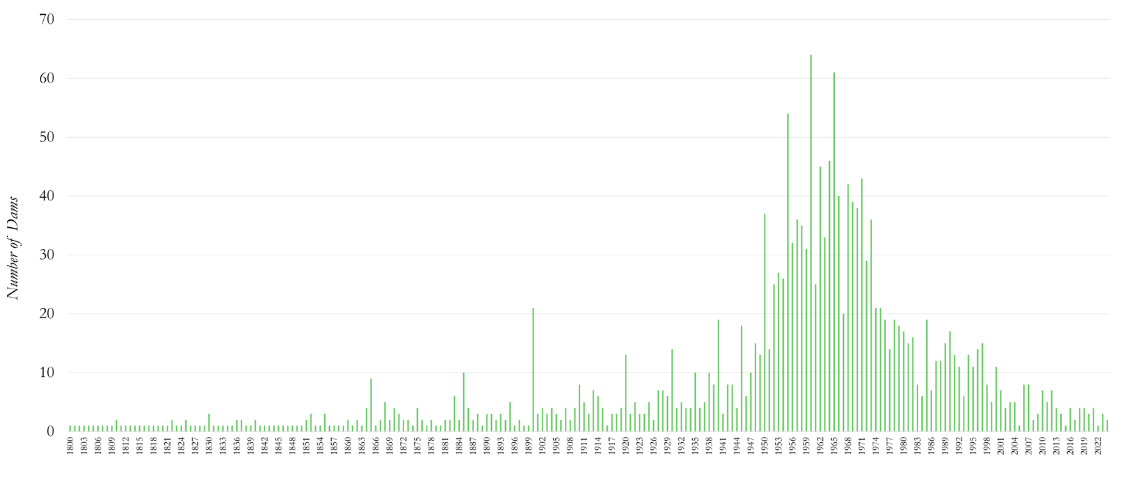
Next to pipe breaks, there is also the "slow-drip" but significant impact of leakage. As already mentioned in Chapter 1, water systems lose about 7 billion gallons of water — more than 10,600 Olympic-size swimming pools — each day. There is much less publicly available information on the state of private water systems, but they are built around the same time as the public ones, and underfunding for upgrades has been reported. One could therefore imagine that at least some parts of the private water system are in less-than-optimal state of upkeep too.

Pipe updates are underway by now, albeit with a slow start. In 2019, water utilities were replacing their pipelines at an annual rate of about 1% to 5%[121] . Efforts have recently been stepped up significantly, however. New regulatory priorities, including the Bipartisan Bill, have allocated a partial amount of the necessary funding, estimated at over $300 billion for replacement of pipes alone, for states to invest in their local water infrastructure,[122]. And October, 2024, in what the National Resource Defense council called "a monumental victory for public health and our children", the EPA released the Lead and Copper Improvements Rule that requires nearly every lead water pipe in the nation to be removed within the next 10 years[123] .

Aging dams

The number of the estimated high-hazard dams also has increased over the past two decades. Dam failure is typically a consequence of overtopping (flooding), intentional harm, poor construction, and inadequate maintenance over time[124]. A well-known case of dam failure occurred in Johnstown, Pennsylvania during the 1800's which led to the death of more than 2,200 people and severely deteriorated local infrastructure, the environment, and freshwater sources[125]. The Federal Emergency Management Agency (FEMA) estimates that 27,000 dams are at risk of failing in the coming years (without necessary maintenance and repairs), which poses significant risks to local communities and ecosystems, as well as real estate properties and other infrastructure types. There are now 2,300 dams with high hazard potential and no emergency action plan (EAP), as shown in Exhibit 22. While this figure seems low compared to the 91,886 dams across the nation, it is important to note that 76% of dams are classified as high hazard potential but have developed an emergency action plan, mitigating the risk posed by these structures[126] — although not eliminating them.

Exhibit 22. High hazard potential dams by construction year. Note that the average life expectancy of dams is 50 years. Also note that these are high risk dams without an emergency action plan (EAP). Dataset from National Inventory of Dams (2024).



119) ASCE (2021)
120) Center for Sustainable Systems (2023b)
121) ASCE (2021)
122) Truth From The Tap (n.d.)
123) National Resource Defense Council (2024)
124) Federal Emergency Management Agency (2016)
125) Federal Emergency Management Agency (2016)
126) National Inventory of Dams (2020)

Other physical parts' age
There are about 7,000 recorded levee systems in the US, although they are estimated to be several thousands more private ones that are not officially registered[127]. Most levees too are considered to be in serious need of repair; the average age of levees is 59 years, while the average lifespan is 50 years.

Wastewater treatment machinery has a lifespan of around 15-20 years while sewage systems' lifespan is around 50 years[128]. Water and wastewater treatment facilities came about in the late 1900's because of new environmental standards. POTW are sometimes also reported to be outdated and weakening, and although there is no evidence of being in the alarming condition of pipes and dams at the moment, they will require replacement or repair in the upcoming years[129].

Aging workers
Another issue related to aging is pending retirement of a large part of the water infrastructure's workforce. On average, drinking water and wastewater workers are 48 years of age – several years above the overall national average of 42[130]. One-third of field employees will retire in the next 10 years, presenting a risk of considerable knowledge loss on how to operate and manage the physical parts of the US water system.
There are relatively straightforward solutions to these physical infrastructure and workforce age-related challenges, all of which require significant financial investments. This brings us to the next challenge: lack of funding.

Insufficient investment capital
The financial capital required for the repairs /replacement of all physical parts and upgrades to drinking water and wastewater infrastructure in order to meet federal water quality and safety requirements is estimated by the EPA to be at least $744 billion over a 20-year period[131], with some putting this number closer to $1.2 trillion[132]. Although water utilities generate revenue from charging fees for supplying water, many struggle to come up with the necessary investment capital for maintenance or upgrades. Smaller Community Water Systems (CWS) especially face funding challenges, due to smaller revenues and overall fewer resources. The decentralized management and varying sizes of water systems has further impeded coordinated efforts to renew and repair water infrastructure. Federal and state governments have historically shared part of water systems' funding burdens; however, this support has also been historically deficient. There are a few dedicated State Revolving Funds (SRFs) and a series of other assistance programs, but for the most part, states allocate budget for water infrastructure from general state funding, and not seldom competing priorities prevail. A point of contention with the EPA-administered federal programs seemed to be prioritization projects for new construction or technologies rather than for repair and replacement of traditional infrastructure[133] . Although it should be noted that these federal funds have seen changes in rules and a significant influx of funding recently, as discussed in the next chapter on the regulatory landscape.

While the issue of underfunding is primarily associated with public utilities, there is concern about the aging infrastructure in privately owned water systems too — despite much less available information — as these industrial facilities face similarly harsh budget-constraints when it comes to necessary maintenance and upgrades. Bigger water systems are generally considered to be more on track when it comes to maintenance and upgrades. Ten of the largest private water companies in the US, for example, recently invested more than $3.9 billion to ameliorate outdated water infrastructure parts with things such as new pipes and digital technology that would enable more efficient water use[134]. On the other hand, smaller facilities or the more outdated ones in particular may be financially unable to upgrade their systems and machinery. This constitutes an undesired reinforcing feedback loop where limited financial means for upgrades keeps eating away at future profitability and sustainability, a dynamic that will come back later in this document. It also impedes regulatory compliance for water standards, a challenge that is discussed next.

London Avenue canal, pumping station, flood gates and levee, in New Orleans, Louisiana.

127) Shapiro (2023)
128) Center for Sustainable Systems (2023a)
129) Copeland (2010)
130) EPA (2020)
131) Humphreys & Ramseur (2022)
132) Mills & Oberthur (2024)
133) Copeland (2010)
134) Truth From The Tap (n.d.)

Water quality & regulatory compliance

Aging infrastructure and insufficient funding often hinder adherence to regulatory frameworks. Meeting water quality standards set by the Clean Water Act (CWA), Safe Drinking Water Act (SDWA), or maximum contamination level (MCL) standards, require things like uncompromised physical networks and consistent monitoring of water quality along the way. Lead contamination is a common example: main pipe breaks, corrosion, and inadequate lead level tracking can result in lead presence in drinking water. Stormwater runoff management is another challenge – and rising along with the effects of climate change. While a lot of precipitation might sound like a good thing in a warming an overall drying climate, more water than the infrastructure can handle does more to pollute water pools rather than contribute to it. Excess water requires more water absorption, storage, and treatment capability, increasing the burden on facilities. According to the most recent "Clean Watersheds Needs Survey" conducted by the EPA, clean water infrastructure needs dealing primarily with wastewater and stormwater have risen 73% over the past 10 years[135] .

Industry challenge

For industrial water in particular, quality is a challenge. The wide range of activities across different sectors complicates water reuse[136]. All industrial water users must adhere to some uniform water quality standards set by the EPA, but additional industry- and activity-specific regulations based on contaminants they may introduce into water sources are required as well. While these do exist, due to industry confidentiality, many facilities do not transparently disclose the types of pollutants their operations generate, nor the status of their water quality[137]. PFAS, again, is one example, as it is a byproduct of a large share of manufacturing operations Yet, until recently, there was no regulation on disclosure of PFAS for manufacturers, despite scientists finding the presence of this potentially harmful substance in water ubiquitous[138].

Photo of water samples taken for PFAS contamination testing.

While not straightforward, there is much more that can be done in terms of best practices on efficient and least polluting water use (the activity- and sector-specific details of which are beyond the scope of this paper)[139]. Apart from incentives related to reputation, community acceptance, and long-term viability of business

Box 2. The mining sector and water

The US mining sector is a salient example of the infrastructure challenges discussed so far. There are approximately 13,000 active mines in the US. Unlike in most other industries, mining facilities predominantly use saline water for their operations, usually from the ocean. While mining operations only account for 1% of freshwater use, they are still among the most hazardous and polluting activities for freshwater pools and the environment in general[143].

Mining facilities utilize a network of pipes spanning for miles to transport water from the shore to their often remotely located facilities. Apart from this requiring large amounts of energy, it also introduces many risks for surrounding water pools due to potential leakage or breaks. Mining operations are highly invasive, including techniques like fracking (drilling deep into the ground, filling the space between the rock with casing and cement, and injecting a mixture of water, sand, and chemicals at high pressure) to retrieve fossil resources, metals and minerals. Leakage during the process, leakage of tailings (the leftover materials) during storage, and even depositing tailings without proper treatment, severely deteriorate freshwater supplies with toxic, acidic, and radioactive chemicals[144]. According to the Center for Biological Diversity, improperly treated wastewater from mining activities has compromised the health and quality of more 12,000+ miles of US rivers and 180,000 acres of lakes and reservoirs[144] . Yet, regulation or governance are often claimed to be inadequate for this industry[146]. Additionally, many of today's mining facilities are outdated and lack the proper digital and physical infrastructure to track water quality. Outdated infrastructure also means that the amount of water used is not adequately tracked, and water waste is thus another major challenge faced by the mining industry. Some scarce estimates for the Minerals, Mining, Metals (MMM) industrial sector estimates evaporative losses of water to be as much as 25%, accounting for approximately $200 million annually[147] .

In many cases, the adoption of advanced digital technology and other ecologically engineered solutions may enable these (and other industrial) facilities to increase their water efficiency, improve wastewater treatment, and reduce their environmental footprint. Such digital solutions are explored in greater detail in the Synergies section.

Polluted mine waste draining into Red Mountain Creek, Uncompahgre National Forest, Colorado.

135) EPA (2022)
136) Meese et al. (2022)
137) Meese et al. (2022)
138) United States Geological Survey (2023b)
139) Singh et al. (2023)
143) American Mine Services (n.d.)
144) American Mine Services (n.d.)
145) Center for Biological Diversity (n.d.)
146) Witchalls (2022, April)
147) Leonida (2019)

activities (which sometimes are simply too weak to affect corporate behavior sufficiently), there is a rising incentive from the regulator side. While water quality regulations themselves as well as their enforcement of have been criticized as too weak in the past[140], over the past few years the EPA has broadened standards to include new compounds and tightened existing ones. For example, new EPA regulation in 2024 on PFAS established the requirement to track and disclose these substances in manufacturing[141]. Fines have been increased, and enforcement efforts stepped up. For example, in 2023 the EPA increased the numbers of "correcting violations" by 300% over the prior 10-year average[142].

Water scarcity

Apart from the quality, there is the quantity aspect of water use. As already described in the previous chapter, water use in the US is unsustainably high, especially given other trends of a warming climate and growing population. Municipalities and industries will be increasingly challenged by water scarcity and the need to track water usage and losses, particularly in water-stressed areas. While there is no direct regulation in terms of water efficiency mandates or capped amounts, standards on best practices and disproportionate water price increases along with higher use to minimize water footprints in households and industry could be part of a more holistic policy framework, a subject we'll come back to in the next section and Synergies chapter. There are also more direct, singular steps that municipalities and industrial organizations can take, like addressing losses from evaporation, leaks and breaks. Data on water loss and inefficiencies in the industrial and other private sectors is not readily available, as many entities either do not disclose or are unaware of the full extent of their water usage. But municipal estimates include a 16% daily loss rate for wastewater and an estimated 11% of water loss due to leakages[148], which would suggest a similar range of water loss within the industrial sector.

As a matter of fact, companies around the world recognize the importance of water for their operations and the potential risks associated with its scarcity. Almost 6 out of 10 respondents to a 2018 Carbon Disclosure Project (CDP) survey reported exposure to substantive water risks either in their direct or indirect operations, with almost 1 out of 10 indicating that the majority of their facilities were exposed[149]. 30% of respondents experienced detrimental business impacts from water issues, resulting in a total financial impact of $82,775,939 — significantly more than the reported $2,451,955 in penalties, fines, or enforcement orders for quality issues. Overall, water issues related to quality and quantity combine into serious threats for company-viability, on top of the already sufficient threats to human and ecological health. In 2018, for example, global companies collectively incurred a $38.5 billion in losses due to water-related issues, which included both scarcity-related issues as well as regulatory ones for compromised quality[150]. And in 2022, water depletion and contamination resulted in $15.5 billion stranded assets worldwide, mostly in the oil and gas, electric utilities, coal, metals, and mining industries[151].

Exhibit 23. Water-related financial impacts from companies around the world.

Financial Statistics on Global Companies

$15.5 billion
corporate stranded assets by disruption to water access (e.g., from community opposition or changes in water regulation) in 2022 of which
$13.5 billion
are in the oil and gas, electric utilities, coal, metals, and mining industries

30%
of CDP reporting respondant companies faced penalties, fines, or enforcement orders due to water-related issues in 2018 with a financial impact of
$82.8 billion

6 out of 10
of CDP reporting respondant companies exposed to substantive water risks in their direct/indirect operations in 2018
$38.5 billion
in losses due to water-related issues

Cybersecurity

Recently, cybersecurity threats have gained significant attention, also within the water infrastructure space. In the past couple of years, at least three cyber-attacks targeted water infrastructure[152]. If successful, such an attack may interrupt water treatment process and/or storage, damage pumps and valves, alter the chemical levels in water to hazardous amounts, and impede communication between operating machinery, with the potential end-result of disruption of a region's functioning and even direct damage to public health. While some might imagine that the most digitized water systems carry the highest risk, the opposite is true. Some digital technology is already present the machinery and other equipment in any water system. It is the outdated, often smaller, water systems therefor that are particularly exposed, given their relative lack of sophisticated digital and financial capacities. The major points of access for cyberattacks are vulnerabilities like a facilities' network configurations, media protection, or remote access[153]. Human error is a major issue as well, when policies and procedures are not well-designed or communicated or staff is poorly trained on the issue, such as when water utilities forget to change default passwords, use single logins for all staff, fail to remove access of former employees to their facilities, or lack cyber-resilience assessments[154] .

140) E.g., Duhigg (2009)
141) EPA (2024a)
142) EPA (2023)
148) Barfuss (2023)
149) Carbon Disclosure Project (2018)
150) Gerber & Fedotova (2023)
151) Gerber & Fedotova (2023)
152) CBS News (2024)
153) Clark et al. (2016)
154) EPA (2024d)

For example, the Cyber Av3ngers successfully led a cyberattack on a small water utility in Pennsylvania, causing it to switch from remote to manual pumping[155] . Another attacker known as the Volt Typhoon successfully led a cyberattack that affected a series of interconnected infrastructural networks including a water utility, leading to the misconfiguration and short-term dysfunction of these critical systems.

In response to this rising threat, there have been initiatives to implement risk and resilience assessments in water supply systems. Section 1433 of the Safe Drinking Water Act (SDWA) requires the implementation of Risk and Resilience Assessments (RRA) and the development of Emergency Response Plans (ERP). However, due to a lack of financial and other resources, most water utilities (70%) so far have reportedly been unable to comply with this mandate[156].

This interconnection with the broader trend of digitization and cybersecurity is not the only relevant one for the US water infrastructure. In fact, it's not even among the most important connections. This brings us to another important aspect of the water infrastructure: its interdependence.

Connecting

It's vital to have a look at the overall system a subsystem is part of sometimes, to identify any major contagion risks from outside of the subsystem, or conversely, potential situations where relatively small risks travel outside of the subsystem's boundaries to compound in the bigger one and come back significantly amplified. Not all risks from the bigger system are necessarily important, but here we'll touch on a few potentially strong connections.

Firstly, the US water systems are a part of the overall US infrastructure, which also includes transportation and civil infrastructure. And many of these other parts that the water system depends on (and supports) are also reaching their age threshold. Any kind of failure in these other parts, say a collapsing bridge, could potentially compromise transmission pipelines and other water infrastructure components as well[157]. This is why the Bipartisan Infrastructure Law (BIL), as will be addressed in more detail in the next lens, takes a holistic approach towards revitalizing water infrastructure as part of the overall US infrastructure with several investments and funding opportunities.

Many succesful cyber attacks are due to human error.

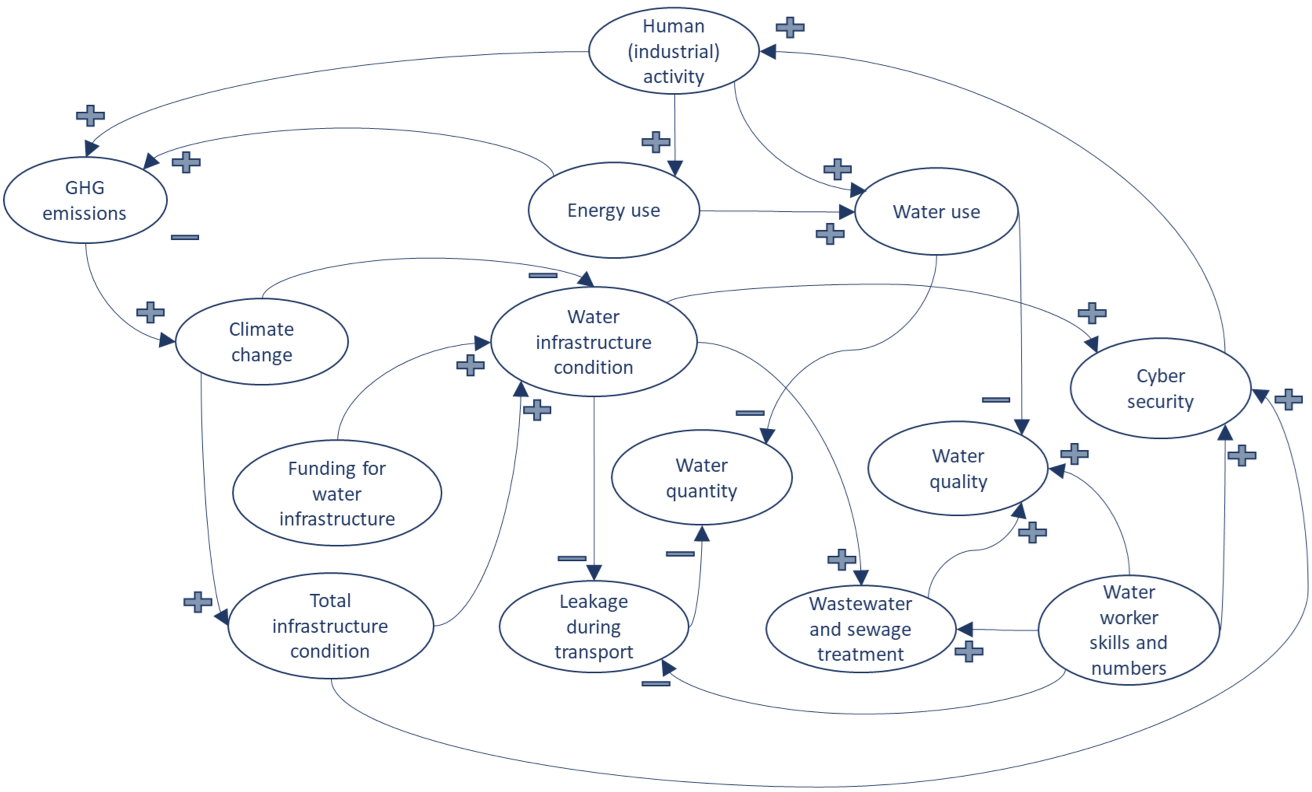
155) CBS News (2024)
156) EPA (2024d)
157) Van Leuven (2011)

Secondly, there are interconnectivity risks from the overall society that the infrastructure is part of, and the ecosystem that society in turn is embedded in. The nexus of water, climate change, and energy is a noteworthy case in this context. As mentioned at the beginning of this section, energy generationtakes the biggest share of freshwater withdrawals in the US. At the same time, water treatment, water distribution, and wastewater treatment require substantial amounts of energy. There are the pumping stations along distribution systems that require energy to power, there's the monitoring and tracking technology, the aeration or sludge processing in wastewater treatment facilities, and the list goes on. Water treatment uses 2.069 kWh per 1,000 gallons of water, for wastewater this figure is 2.521 kWh(158). In total, US water infrastructure accounts for about 2% of total electricity use, and almost half of operation costs for water utilities comes from energy demands(158).

Since not all of this energy is generated from renewable sources, water use also contributes to climate change. Approximately 0.7% of total US GHG emissions are emitted by wastewater treatment facilities(160). Climate change in turn puts further pressure on water availability and quality in a myriad of ways, as already discussed in the environmental lens. In addition, extreme weather events may end up damaging the physical aspects of water and other infrastructure, for example by inundating treatment facilities or causing disruptions along the water distribution system. More frequent and intense rainfall also poses the threat of overwhelming the outdated water system. Wastewater treatment plants, for example, manage storm runoff and treat excessive water from flooding, but are ill-equipped to process the already growing quantities of water. In layman's terms: sewers may overflow. This can lead to, among other things, harmful organic and/or chemical compounds washing into public spaces. Excess rainwater will also flow off roads, parking lots, rooftops, and pavement, on their way down collecting substances which will compromise the health of aquatic life in the water bodies they eventually end up in(161).

This climate adaptation aspect is partially related to outdatedness of the water infrastructure, which in a way brings us full circle. We are now ready to for the causal loop diagram (CDL) of the main technical aspects discussed in this chapter. Next is the last lens, with the social interactions.

Exhibit 24. Causal Loop Diagram (CLD) of technical interactions.



158) EPA (2023, August)
159) EPA (2017b)
160) Center for Sustainable Systems (2023a)
161) Water Science School (2018a)

Social lens

This last lens covers the regulatory, economic, and behavioral dimensions. The main regulatory schemes and authorities governing water infrastructure in the US are discussed, as well as the impact of the BIL, also called the Infrastructure Investment and Jobs Act (IIJA), on regulatory frameworks and infrastructure investments. This section also covers the dynamics between affordability and availability concerns of water, as well as public perceptions on water quality, conservation, and infrastructure. A last note on the interconnections between the covered social aspects round out the chapter.

Regulatory landscape

Public utilities are regulated at the federal level and also have to concern themselves with a myriad of state and possibly local regulations. Private water systems fall mainly under state authority[162]. The extent to which these private water systems are regulated shows large variation among states; Wisconsin has the most comprehensive authority over private systems, while public utility commissions in Georgia, Michigan, Minnesota, North Dakota, South Dakota, and Washington, D.C, have none. A more detailed overview of state regulations on private water systems is beyond the scope of this document, so this section will focus mainly on the public water systems.

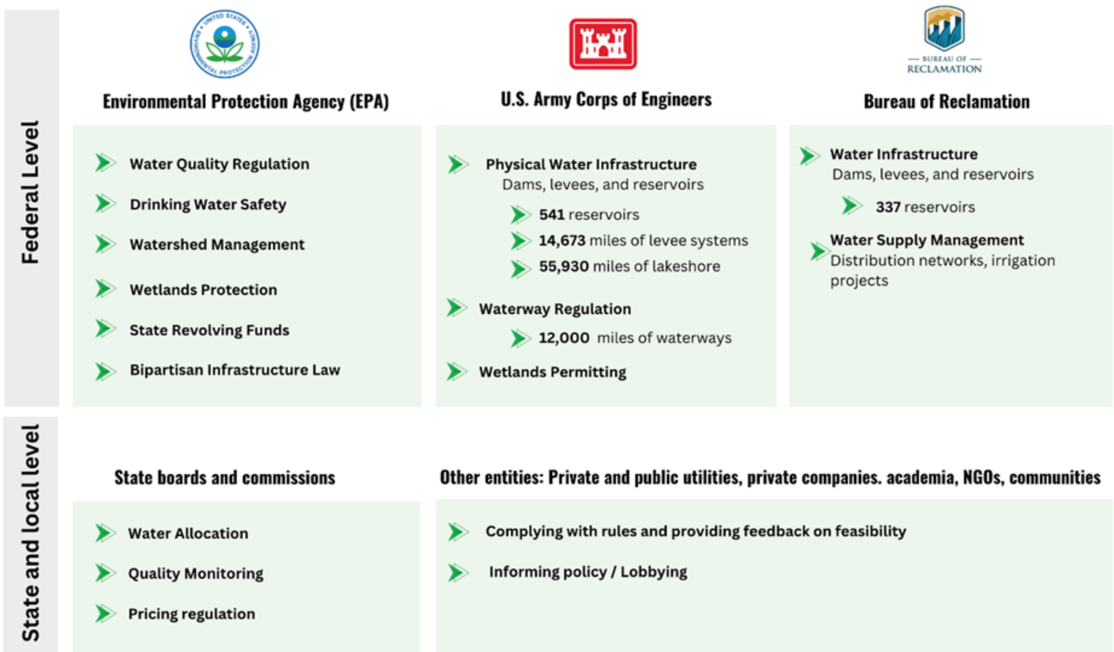
Regulating authorities

There are three main federal agencies governing the US' public water resources: the EPA, USACE, and the US Bureau of Reclamation[163]. The EPA oversees a wide range of responsibilities related to the environment and public health. When it comes to water, the EPA has the widest authority, administering both the Clean Water Act (CWA) and the Safe Drinking Water Act (SDWA). The EPA also provides funding for water infrastructure projects and administers other regulations aimed at maintaining water quality and environmental health. Adjacent to the EPA, the USACE and the US Bureau of Reclamation operate and manage water resources and parts of the physical infrastructure. The US Bureau of Reclamation, a subsidiary of the US Department of the Interior, constructs and manages essential water infrastructure like distribution networks, irrigation projects, and 337 reservoirs. Similarly, the USACE manages 541 reservoirs across the country and is responsible for 14,673 miles of levee systems, 12,000 miles of waterways, and 55,930 miles of lakeshore.

Beyond federal agencies, states are responsible for price regulations on public water systems, ensuring regulatory compliance, securing funding, and maintaining essential water infrastructure. State economic regulation and utility commissions have authoritative power to ensure price-setting outcomes are just, although their powers vary among states. Details about different pricing schemes are discussed in a later section on economic incentives. Many states work though approval, meaning the utilities submit their pricing schemes underpinned with analysis showing cost of service, user trends and projections, financial availability, planned maintenance, etc.

Other entities influencing water infrastructure policy in the US include public utilities, private sector companies (manufacturers, firms, private water companies), Non-Governmental Organizations (NGOs) like the US Water Alliance, and the public/communities, not just as voters but also al co-owners of the about 3,300 water cooperative water systems in the US.

Exhibit 25. Key players in the regulatory landscape of water infrastructure.



162) Bowen et al. (2019)
163) U.S. Government Accountability Office (2014)

Key regulations

Regulations for water quality and quantity differ in strength and which level of government is setting and enforcing the regulations. Aspects of water quantity are regulated at state level or merely incentivized rather than mandated. Quality is the most regulated aspect of water, as laid down in federal law.

Water quality

The CWA is the most important (and oldest) law that sets a national standard for water quality[164], for which the EPA serves as the primary governing authority. The goal of the CWA is to achieve fishability, drinkability, and swimmable conditions, of freshwater bodies in the US. The CWA establishes Maximum Daily Loads (MDLs) for an array of contaminants in drinking water. An amendment to the CWA, the National Pollution Discharge Elimination System (NPDES), establishes an MDL standard for the maximum number of contaminants in water allowed. States are required to monitor, track, and report levels of contaminants or pollutants in water bodies. The SDWA, also administered by the EPA, safeguards water quality by establishing national standards deemed safe for consumption[165]. Public Water Suppliers (PWS) must comply with SDWA standards and must report back to the EPA. Other relevant policies set by the EPA include the Lead and Copper Rule, which requires water systems to test and treat lead found in water, and the Underground Injection Control regulation, which protects water quality by banning the injection of wastewater into groundwater sources[166].

Water quantity

When it comes to water quantity, there is regulation on two main aspects: allocation and efficiency. Water allocation is governed at the state and local level, which means there is some level of forced compliance, but the rules are not uniform across jurisdictions. Water efficiency standards vary even more, with the federal government working more with certification as of now than mandating, some states like California going further in water efficiency laws, and some states without any additional standards.

Allocation

Water allocation is determined at the state level and by either one, or a combination of, two basic legal doctrines: Riparian Rights and Prior Appropriation[167]. The Riparian Rights doctrine establishes water allocation rights based on location – these are tied to land ownership, meaning that owners of land bordering a body of water have the right to use that water with "reasonable use". Unlike Riparian Rights, the Prior Appropriation doctrine is based on a first come, first serve basis: water rights are granted to the first person to redirect and use water for beneficial purpose; without use, these rights may be lost[168]. Generally, Western US maintains Prior Appropriation rights as the guiding doctrine in freshwater allocation while Eastern US usually adheres to the Riparian Rights doctrine. When it comes to groundwater allocation, both Riparian Rights and Prior Appropriation doctrines are sometimes combined into a hybrid system.

When bodies of water cross state lines, interstate compacts or contracts between two or more states may have to be adopted to determine how to manage water and ensure compliance with state-level and federal-level regulation. If this cooperation is done well, it can yield considerable benefits both in terms of water availability as well as sustainability. The Great Lakes-St. Lawrence River Basin Water Resources Compact is an example of this. It's an agreement between eight US states to protect, conserve, restore, improve, and properly manage the Great Lakes[169]. The Great Lakes compact established a clear governance structure, stringent water conservation requirements, and facilitated water resource cooperation between states. In 2016, the Great Lakes Compact approved Waukesha, Wisconsin's request to divert contaminated water originating in Waukesha to Lake Michigan. The request was approved under stringent conditions including a requisite that all water diverted must be returned to its source, which ended up being met[170].

Sleeping Bear Dunes National Lakeshore, Michigan.

Efficiency

The Energy Policy and Conservation Act, enacted in 1992, set mandatory maximum water flushes and flow rates for newly manufactured toilets, showerheads, and faucets. Technology is capable of more efficiency these days[171], adoption of which the EPA is mainly incentivizing though labels and certifications [172]. Some states have set their own water efficiency standards, with California going the farthest by requiring stricter and wider applied efficiency standards for all new constructions, both for water and energy use[173]. These standards apply mostly to end-users, while the topic of water infrastructure brings a focus leaning more towards the supply-side. Although we will not go beyond a brief mention for that reason, water efficiency standards can significantly reduce total water demand — and have done so[174] — which is relevant enough for the overall issue of water scarcity to deserve a brief mention here.

164) Reimer (n.d.)
165) Reimer (n.d.)
166) U.S. Government Accountability Office (n.d.)
167) U.S. Government Accountability Office (2014)
168) U.S. Government Accountability Office (2014)
169) National Center for Interstate Compacts (n.d.)
170) Alliance for the Great Lakes (n.d.)

Funding

There are several funds to supplement the revenue stream from water fees for water utilities, with varying focusses and provided at various levels of government.

The largest funds are the EPA Clean Water State Revolving Fund (CWSRF) and the Drinking Water State Revolving Fund (DWSRF). Both these EPA-managed funds provide low-interest loans and grants to municipalities to help them comply with the CWA and the SDWA, respectively[175] . To date, the CWSRF has provided $172 billion to communities[176]. A cumulative total is not provided for the DWSRF, but it reports $4.4 billion in assistance to communities for 2022[177]. Loans provided by the CWSRF and DWSRF may be used to maintain, upgrade, or renew water infrastructure (and maintain water quality) including distribution networks, pipe replacement, and wastewater and water treatment facilities[178]. Monetary allotments from the DWSRF come in the form of a 20% funding match and are determined by the Drinking Water Infrastructure Needs Survey (DWINSA). The DWINSA is a statistical survey of US public water systems conducted every four years, to determine priorities in water infrastructure. In 2023, about 3,629 public water systems were selected[179]. Likewise, for CWSRF loans, the states contribute an additional 20% to supplement the federal grants[180]. Besides the SRFs, the EPA administers the Water Infrastructure Finance and Innovation Act (WIFIA) program, a federal loan program that aims to accelerate investment in water infrastructure and provides long-term, low-cost additional loans for water and wastewater infrastructure projects. It offers large projects ($20+ million) financial assistance to bring forth improvements in water and wastewater infrastructure projects as well as incentivize private-public sector collaboration[181].

Outside of the EPA, the USDA Rural Development agency administers more than 40 programs for improving the US' water infrastructure landscape, focusing on rural communities. The Water and Environmental Program (WEP), as an example, provides loans, grants, technical assistance, and training for water infrastructure building capacity in communities of less than 10,000 residents[182] .

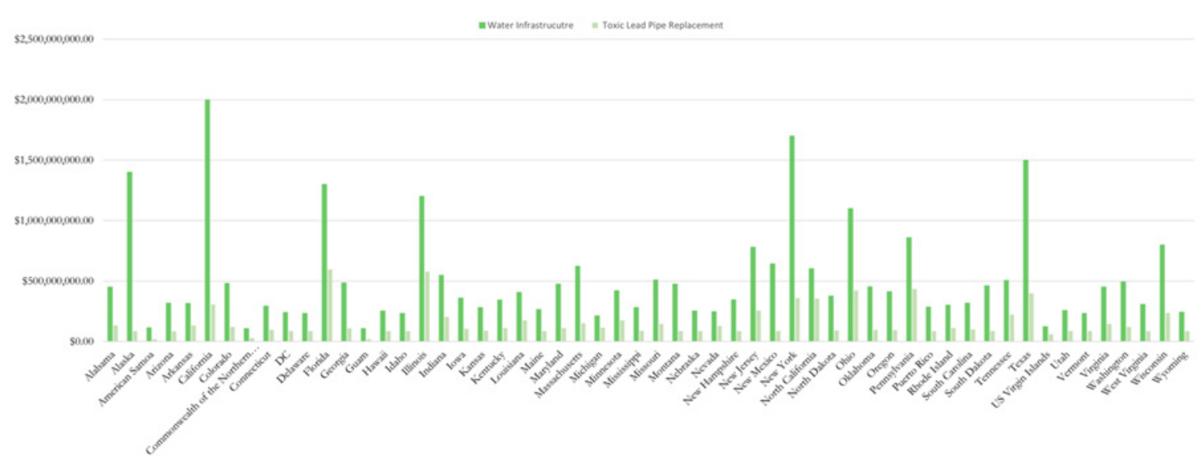
State budgets are another source of funding, where a portion of tax revenue is allocated directly to water infrastructure improvements. The California Department of Water Resources, for example, lends money to local water agencies at low-interest rates for improvements to water management, water conservation, groundwater storage, and water quality[183].

While water policymaking is a continuous process like any other societal matter, the Bipartisan Infrastructure Law (BIL) stands out as a significant recent push from the federal government to boost financial support for water (and other) infrastructure. While experts stress that the BIL only provided about 9% of what's needed to ameliorate the country's water infrastructure[184], it is a significant step in the right direction that merits a more detailed discussion.

Bipartisan Infrastructure Law

In 2021, President Biden signed the BIL to support US infrastructure with $550 billion over a 5-year period, about 10% of which was dedicated to water infrastructure specifically. The $55 billion enhancement to the aforementioned funding mechanisms are aimed at upgrading the US' water infrastructure, improving compliance with water quality standards, replacing aging lead pipes, improving wastewater and sanitation infrastructure, and alleviating disparities in water accessibility[185] . Exhibit 26 shows the amount of funding granted to states by the BIL and the proportion of that funding that was allocated to toxic lead pipe related projects.

Exhibit 26. BIL Funding for water infrastructure by State. Note that the toxic lead pipe replacement amounts are included in the total water infrastructure funding amount. Data from The White House State Fact Sheets (n.d.).



171) Alliance for Water Efficiency (2023)
172) EPA (2024e)
173) Alliance for Water Efficiency (2023)
174) EPA (2024e)
175) Reimer (n.d.)
176) EPA (2024e)
177) EPA (2023, October)
178) Reimer (n.d.)
179) EPA (2023, September)
180) EPA (2024f)
181) ASCE (2021)
182) ASCE (2021)
183) California Natural Resources Agency (2016)
184) Galante-Johnson (2024)
185) The White House (2024, February)

About $30.7 billion of the BIL funding is allocated towards the DWSRF, with the goal of replacing lead service-lines ($15 billion), investing in other unearmarked water projects ($11.7 billion), and addressing PFAS ($4 billion)(186). Another $5.5 billion was allotted to emerging contaminants under the SDWA act for drinking water. $12.7 billion is allocated towards the CWSRF for additional grants to address water pollution ($11.7 billion) and emerging contaminants ($1 billion) as covered in the CWA. Ultimately, the funding provided by the BIL is estimated to increase the annual average of water-related projects for the DWSRF from 700 to 3,500, and from 1,300 to 2,600 projects for the CWSRF.
The remaining $6.9 billion was allocated towards other projects including $1.4 billion to manage stormwater and sewer overflow, $925 million to build more resilient and sustainable infrastructure, $700 million towards lead-reduction programs, $700 million towards improving water affordability, accessibility, and availability, and finally $250 million towards the Indian Reservation Drinking Water Program(187).

An important aspect of the BIL is its focus on disadvantaged communities. Almost half of the funds (49%) allocated towards the DWSRF and towards lead service line replacement will go to communities confronting environmental justice concerns, low-income communities, or communities of color, in the form of forgivable loans(188). Similarly, 49% of the funding for the CWSRF must go towards projects in disadvantaged communities and must be in the form of forgivable loans/grants, and 25% of the funding through the DWSRF Emerging Contaminants Funding must be available for disadvantaged communities as forgivable loans / grants.

There have been significant advances within the water infrastructure space thanks to the BIL. In 2023, around $21.9 billion of the total funding amount had been provided for water infrastructure repairs(189). BIL funding has enabled 1,400 new drinking water and wastewater projects across the US, 800 of which are delivering safe and clean water to tribal communities that previously lacked access to effective water infrastructure(190). Additionally, a 300-mile water distribution system – Lewis and Clark Rural Water System – running through rural Minnesota, South Dakota, and Iowa has been set into motion, expected to deliver clean water to 350,000 residents in these areas.

Apart from physical upgrades, the matter of affordability was also explicitly addresses in the BIL. Clean water that is also affordable for all communities is an ongoing issue in the US. Because it lives on the intersection of various environmental, technological, and social aspect arounds water, including economic ones, this is a good point to engage in a further exploration of the topic. The economic incentives will be discussed first, after which other social factors will be addressed, including public attitudes and the sometimes-crucial role they play in shaping sustainable water systems.

Aerial View of the Standing Rock Native American Reservation in North and South Dakota.

186) Bielenberg et al. (2022)
187) Bielenberg et al. (2022)
188) EPA (2022, March)
189) Tomer (2023)
190) The White House (2024, May)

Economic incentives and costs

Addressing the challenges of water infrastructure in the US requires a comprehensive understanding of the costs, investments, and potential savings across the economic spectrum. These incentives can vary depending on the stakeholder's perspective. Savings could include a reduction in financial costs because of less water leaks for utilities. For citizens, it could be avoided health damage or less money spent on bottled water thanks to being able to trust the tap water's safety. For a government body, it could be reduced budget spending on health care costs. Such an understanding is necessary for identifying possibilities to organize the US water system so that adequate funding for upgrades to infrastructure, more equitable access and affordability, and efficient use are incentivized.

Attention has been given already to funding needs, challenges, and options of water systems—the supply side. While this focus made sense given that the physical parts of the water infrastructure reside on that side, when it comes to economic and other social incentives, the demand side 's behavior shapes the options for the supply side to such a degree that they will receive a bit more attention in the following sections. Of course, the supply side very much shapes the options for the demand side as well. Water users, i.e., all of us, to a significant degree cannot reduce their use even at high prices. This can create a trade-off between affordability and availability, which is discussed next. The main way to try to balance this trade-off has been different ways of water pricing as covered subsequently, followed by some other initiatives, water markets and financial assistance.

Water availability and affordability

Water *availability* is determined by the physical quantity of water, infrastructure, and environmental conditions that enable a population to meet its water demands. Water *affordability* refers to the ability of households to pay for water services without facing financial hardships and/or having to (partially) give up another basic need. There can be a trade-off between the two. For example, higher water prices will incentivize more frugal water use and provide more funding for infrastructure maintenance, thereby strengthening availability. But higher prices may also price out low-income households from access to the full amount of water they need, thereby worsening affordability. The US, like most other countries, is facing this balancing challenge as aging infrastructure, environmental degradation, socio-economic disparities, and rising overall costs threaten reliable and equitable access to water for all citizens. At the same time, the issues are more interconnected than the notion of a "trade-off" might suggest.

An estimated 17% of total US households, about 28.3 million Americans, are unable to cover the price for basic water services[191]. That is, they spend a day's salary or more per onth to pay for basic water services. Water unaffordability is especially prevalent in Southeast and Southwest US, where poverty and water stress are more common[192]. In general, the lowest income groups are associated with significantly higher rates of water unaffordability: households with a yearly income of $15,000 generally use 6.8% of their annual household income to pay for water and sewage services, those within the $45,000-$59,999 income cluster spend 1.2%, and households in the $200,000+ group spend approximately 0.3% of their yearly household income on water-related services[193].
Water affordability is influenced by other variables besides income, including age and race, and area. In rural communities, for example, the main impediment to access to affordable and clean water is inadequate plumbing infrastructure, while the concern in urban communities is typically lower water quality [194]. When it comes to race, indigenous populations and non-white communities disproportionally confront issues with both improper plumbing infrastructure and lacking access to clean and safe water[195]. Black households report higher concern with water affordability than others in surveys[196] , for example, while water utilities in areas with primarily Latino populations were 25% more likely to violate water quality standards[197]. Additionally, a disproportionate number of cases of non-compliance with the CWA and/or SDWA occur in communities with a majority elderly population[198].

An example of the spatial variability and relevance of racial and income inequities when it comes to water affordability and availability is that between the two cities of Jackson City and Brandon, both in Mississippi. According to researchers at the Nicholas Institute for Energy, Environment, and Sustainability at Duke, a household burden above 4.5% means that there is significant water unaffordability[199]. 82.2% of Jackson City's population is black, and approximately 41% lives 200% under the poverty line[200]. Their household water burden, or the ratio of the median water use bill to the lowest quintile of the median income for low-income groups is 4.8%. Comparatively, in Brandon, where 77.81% of the population is white and poverty prevalence is 14.7%, the household water burden is 1.9%, revealing a significantly higher water affordability.

Mayes Lake at LeFleur's Bluff State Park in Jackson, Mississippi.

191) Ashton (2023)
192) Cardoso & Wichman (2022)
193) Cardoso & Wichman (2022)
194) Mueller & Gasteyer (2021)
195)Mueller & Gasteyer (2021)
196) Cardoso & Wichman (2022)
197) Rivera-Diaz (2021)
198) Mueller & Gasteyer (2021)
199) Nicholas Institute for Energy, Environment & Sustainability (2022)
200) Grove (2024)

That said, while there is a correlation between poverty levels and income levels, it's not simply that the lower income areas have higher water unaffordability because they have a harder time paying for anything, including water. Water prices are not uniform across the country and can sometimes show the same disparities as outlined above. Water utilities serving disadvantaged communities often have strong budget constraints impeding them from making necessary repairs to pipes, water distribution networks, and wastewater treatment facilities etc. The resulting water losses and other system inefficiencies put downward pressure on water availability, thus driving water prices up. Other systemic issues like a growing income gap and a rising population in some areas, acerbate this upward pressure on prices[201]. It's not unheard of that this undesired positive feedback loop creates water prices to be higher in disadvantaged communities, rather than lower, as water utilities that are unable to recover the cost of their operations increase prices further, resulting in even less households being able to pay at all, and perpetuating this cycle[202] .

The issue of inadequate plumbing also illustrates how affordability and availability are not the disconnected issues as sometimes presented. When talking about water availability, most often we mean access to not just water, but to clean (fresh) water. In this sense, inadequate plumbing poses a threat to both affordability and clean water availability, because it raises not just funding challenges, but also public health concerns as it impedes on people's ability to maintain proper hygiene and sanitation. Clean water availability demonstrates the same social and economic disparities as affordability. For example, around 0.41% of US households had incomplete plumbing between 2014 to 2018[203]. These 489,836 households were concentrated in Alaska, Puerto Rico, Texas, and Appalachia. The majority of these states, together with New Mexico, were also disproportionally found to lack compliance with SDWA regulation. Similarly, in the Intermountain West, the Upper Midwest, Appalachia, and the lower Mississippi, instances of CWA violations were more common. Overall, states with more tribal/indigenous populations, higher incidences of poverty, greater elderly populations, and with pronounced Latino/Black communities tend to experience higher rates of water unaffordability and may thus lack access to clean and safe water[204]. A similar point can thus be made for outdated pipes in otherwise complete plumbing systems: as already mentioned, old pipes are not just an obstacle for clean water availability though water losses from breaks and leaks, but because the corrosion also increases risk of water contamination, cleaning costs go up and safe water affordability goes down.

One can also see how this interplay might be inverted into a synergy, rather than a trade-off: if pipes are upgraded to a complete, non-toxic, and non-leaking network, both water affordability and availability could be expected to improve in the medium run. It's also worth wondering if the undesired reinforcing feedback loop between bad infrastructure condition and rising water rates could be inverted into one with positive impacts that amplify one another. We will come back to these questions in the next chapter on synergies. First, to be able to analyze them, more information on water pricing is necessary. It's not just a question of the total amount of funding necessary, after all. A key aspect around this issue is which parties should share the biggest funding burden, and financial costs in general [205]. More details on this are discussed in the next section on water pricing schemes.

Hubbard glacier in Alaska

201) Patterson (2023)
202) National Resource Defense Council (2022a)
203) Mueller & Gasteyer (2021)
204) Mueller & Gasteyer (2021)

Water rates

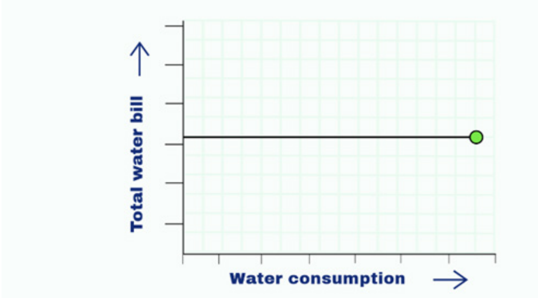
Water rates are the most obvious of economic incentives: direct pricing for use. This has the predictable effect on the demand side; practically every user prefers to pay less rather than more for water. On the supply side, water fees help raise financial capital for a water system's going concern. It might seem at first then that water utilities have no incentive to encourage efficient water use, however, that's not the case. It's possible that an increase in demand necessitates expanding a water system and develop new supplies, which drives up the per unit cost, rather than down[206]. This already common situation is only more likely to occur in the future since water is projected to become less available, as anyone working in water management is aware. This is why water utilities offer resources and incentive programs to spur more efficient use among their customers. The stronger incentive to generate revenue for water utilities, rather than increase use, is to charge higher prices. As mentioned, only a small minority of US water systems are for-profit, but not-for-profits need to stay solvent just the same. When costs increase because of rising scarcity, deteriorating infrastructure, and worsening pollution, water prices will go up — as indeed has been the general trend in the US[207]. For example, between 2010 to 2018, water bills increased by 27%, almost double the increase in the consumer price index over that period[208]. Utilities' ability to increase prices is regulated by state authorities, because water systems can be considered monopolies. As mentioned, the extent to which this authority can be exercised differs between states, which can explain to some degree the considerable variability in water prices between regions or sometimes even a single city[209]. On the other hand, limitations of recovering costs could also be said to explain to some extent the outdated state of water infrastructure. Importantly, however, it is not just a matter of how many costs are shifted onto water users; equally important is how these costs are distributed among them[210]. This happens to various degrees under different water pricing schemes.

There are three main forms of water rate schemes: fixed pricing, uniform pricing, and tiered pricing[211]. Tiered pricing is a container term for several variants, and in most practical cases, some combination of the three main pricing schemes is used for water billing. For clarity, the general principles are explained for each scheme separately here.

Fixed

Under a fixed pricing scheme, the user pays the same rate regardless of their water use. This type of pricing strategy does not require water usage monitoring and does not promote water conservation. It also means that low-income households spend the highest share of their income on water. They are rarely used by themselves in the US, but as will be discussed shortly, are commonly combined with other pricing schemes.

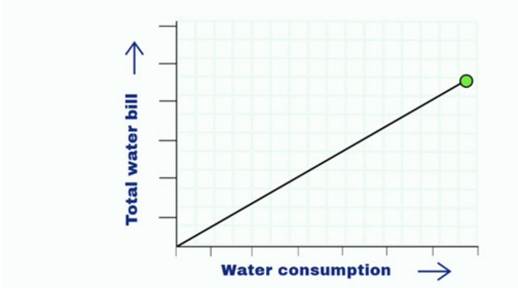
Exhibit 27. Stylized illustration of fixed pricing.



Uniform

Similarly, uniform pricing is the rate at which the consumer pays the same for each water unit. Unlike fixed water pricing, uniform pricing requires water usage monitoring to estimate the final amount payable. This scheme promotes water conservation to some extent, because one pays more with higher water use.

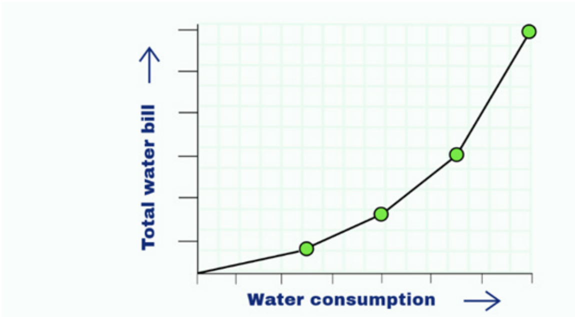
Exhibit 28. Stylized illustration of uniform pricing.



Tiered

Tiered pricing goes further, with a disproportionate price increase with higher water consumption. This scheme thus also requires metering and monitoring. The first price tier is typically intentionally low, to allow for people's basic indoor water use to be affordable. Once users exceed a certain water usage threshold, the price per unit of the additional water used shoots up, serving as a strong incentive to conserve water while also bringing in extra revenue for the utility. This extra revenue is coming from those that could be said to use water excessively compared to others, meaning costs are weighted towards these users rather than all users equally.

Exhibit 29. Stylized illustration of tiered pricing.



206) National Resource Defense Council (2022b)
207) Teodoro & Thiele (2024)
208) Lakhani (2020)
209) El-Khattabi, et al. (2023)
210) National Resource Defense Council (n.d.)
211) EPA (2024g)

Except for tiered pricing in some rural parts of the US — where the tiers go down with more use to accommodate farmers — all variations of tiered pricing are designed to bring water conservation and equitable access goals together. It centers around setting fair tier thresholds, where especially the first tier is intended to be needs-based. The variant where the first tier is determined by several household specifics, such as income and household size, is also often called budget-based pricing(212) . Another variant is lifeline-pricing, which proposes a fixed fee for the budget part, with increasing unit rates above that budget(213). The idea behind this lifeline-pricing is to address conservation and affordability, as well as cash flow predictability, and thus ease of financial planning, for water utilities—another sustainability aspect, which after the sections on outdated infrastructure due to lack of funding should be clear. There are many other variants, including conservation-based rates, which next to affordability also emphasizes price-incorporation of broader societal and ecosystem impacts of water use(214). Time-of-day, seasonal, and drought pricing schemes set prices higher when water use is higher (typically during the day or in summer, for example for lawn watering) or water availability is lower (i.e., in a drought). These can be combined with any of the schemes above, and in fact are often part of conservation-based pricing schemes. A well-known example is the collective shift from utilities to this pricing scheme in California during the 2012-2016 drought(215).

Water tank in Hollywood, California

Execution makes the crucial difference in the effectiveness of tiered pricing. How tiers are structured determines how well different sustainability aspects are achieved; if the tier thresholds are too high, water conservation is not much incentivized, while setting especially the first tier too low will leave the affordability goal unachieved. Some have also argued that the fixed component in lifeline-pricing makes the scheme still somewhat regressive, because the poorest households use less water than what is often considered a needs-based use for the average household, which means the poorest households end up paying a higher per unit price than median-income households (216). Best practices in setting the tiers are a topic of ongoing discussion. Nevertheless, some form of tiered pricing is generally recognized as one of the most effective strategies for managing water demand in a balanced way(216).

Other government initiatives

The main ways that government is influencing water issues in general and water infrastructure in particular have been discussed already. Apart from the various federal, state and local regulations on water's quality, allocation, and pricing, setting of efficiency standards, and of course providing funding for water infrastructure, there are two other ways that government creates economic incentives around water issues relevant enough to water infrastructure that they merit a brief mention: setting up a water market, and financial support for water bills of low-income households.

Water markets

In a water market, water rights between users and suppliers are traded on a platform with the intended outcome of more efficient water allocation through the basic market mechanism(218). The principle is similar to the cap-and-trade markets for carbon: the cap can serve as a limit to consumption necessary for sustainable use at the macroeconomic level, while the resulting market enables quantification and incorporation of water's ecosystem services, creates revenue streams for communities with water resources, and opens additional sources of funding for necessary water infrastructure maintenance and upgrades. An example is the water market in California, which was established in the 1980s(219). A study across several dry states, including California and Texas, found that with the right government conditions, water markets can produce significant water savings, boost overall revenues, improve accountability and transparency in the water system, increase farmer and community resilience for droughts, and restore previously depleted water sources by returning water to nature(220). The Salton Sea, for example, was until recently spared from the mass die-off it has experienced now, because of sustained efforts supported by the California water market to reduce the salt build-up in the region(221).

Designing the water market so that those intended outcomes are indeed realized can get complicated and costly(222). Water rights need to be defined, for starters, and rules on how they

212) Budget Based Rates (2024)
213) National Resource Defense Council (2022b)
214) State Water Resources Control Board (2024)
215) Lee et al. (2024)
216) Smith (2022)
217) National Resource Defense Council (2022b)
218) Hanak et al (2021)
219) California Natural Resources Agency (2016)
220) Richter et al. (2016).
221) Hanak et al (2021)
222) Wheeler et al. (2017)

can be traded. Like the threshold in tiered water rates or the cap in carbon markets, setting the cap for the water market adequately is crucial – and far from straightforward. Use needs to be monitored to ensure not more is taken than was traded. In short, to ensure that the water market indeed creates additional funding for environmental conservation, improves water infrastructure, and supports rather than further exploits communities, a plethora of the right rules around the water market need to be in place. This does come with considerable costs, for taxpayers and market participants. Governments will need to dedicate considerable amounts of public money to the establishment and ongoing regulation of water markets. For small CWSs, the initial capital investment for monitoring and metering technologies necessary to join a water market is not seldom preventively large[223]. There are also non-financial obstacles such as meeting, or even just comprehending, the many rules about pricing structure, eligibility, and what technological and analysis tools should be adopted for monitoring compliance.

Even with the right rules, however, water markets can be a part of a comprehensive policy set to achieve water sustainability in the US, but by themselves will not be enough. Perhaps the fact that in the end, the Salton Sea was not saved, is illustrative of that. More factually, most water in the US is not traded; even in California, which has the most established water market, it's only 4% and trading volume has remained steady for decades now[224]. Apart from moral obligations to treat all water like a commodity, experts agree that around the world and in the US, institutional and other regional circumstances necessary for a well-functioning water market are not present[225].

Affordability programs

Many states and counties have decided to tackle water affordability not just through water prices, but also with direct financial assistance for low-income households. While not directly related to water infrastructure, affordability programs could thus be used as a complement to say, higher water rates —which are used for funding water infrastructure — as a comprehensive package of water policy reform. A relatively well-known example of such a program was the Low Income Household Water Assistance Program (LIHWAP), created in 2020 as part of the federal government's coronavirus response[226]. The LIHWAP ended in March of 2024. One month later, the EPA launched a program that was not necessarily similar but could be said to be complementary, and more focused on empowerment. That program will be discussed in the next section on other social incentives.

Other social incentives and public attitudes

Government can shape behavior in other ways that just via economic incentives, including by raising awareness and clarity around water issues, empowering communities in managing their water resources, and making affordable clean water a policy priority. How well government is perceived to manage water, both in policy design and execution, will influence public perceptions. People's perceptions, in turn, can play an important role in the success or failure of water policies and regulations, including their funding through taxes by grace of the public's "willingness to pay". Americans' attitudes on water issues and trust in how these are managed will therefore also be discussed.

The Salton Sea in earlier times, California.

223) California Natural Resources Agency (2016)
224) Hanak et al (2021)
225) E.g., Edwards & Regan (2022), Wheeler, (2021)
226) Office of Community Services (2022)

Other social incentives and public attitudes

The main ways that government is influencing water issues in general and water infrastructure in particular have been discussed already. Apart from the various federal, state and local regulations on water's quality, allocation, and pricing, setting of efficiency standards, and of course providing funding for water infrastructure, there are two other ways that government creates economic incentives around water issues relevant enough to water infrastructure that they merit a brief mention: setting up a water market, and financial support for water bills of low-income households.

Education

Education can be interpreted as in awareness raising campaigns, or investment in actual skill and knowledge building for pursuing a career in water. As mentioned in the previous chapter, there is a serious risk of losing much know-how in retiring water workers. Indeed, economists and labor specialists pointed out when the BIL was passed, that the touted jobs it would create didn't mean much without additional funding to train people to perform those roles[227]. In July 2024, such funding was made available with the EPA "Innovative Water Infrastructure Workforce Development Grant Program", which provided over $20 million to 13 organizations across the nation[228]. More action was also announced, such as the "America's Water Sector Workforce Initiative" by the EPA, other federal agencies, and various water sector partners with the aim to "collaboratively address the major challenges facing the water workforce sector".

There are also the more general awareness campaigns around water. These are common and typically focus on knowledge about how to conserve water and why it's important to do so, using media like pamphlets, email, social media posts, or booths at festivals. Part of these could also be considered the EPA WaterSense label. The label is not mandatory but does help willing citizens to put any good intentions into practice. All they need to do is look for that label when purchasing a faucet, showerhead, or landscape fixture to conserve at least 20% in water usage compared to similar products[229]. Homes can also get the WaterSense label now, if they use at least 30% less water than the average comparable building, and these labels are claimed to be the most preferred sustainability designation with the majority of homeowners[230] .

Plumber fixing a burst pipe.

Box 3. California's water awareness campaign

One example of an extensive water awareness campaign comes from the state of California, during its 2012-2016 drought and beyond. It contained all earlier-mentioned economic and other incentives, as well as key infrastructure aspects such as strict regulation and allocated funding[231]. California's approach serves as an illustration of the importance of social incentives — spurred by environmental urgency — to complement the economic ones.

When the governor at the time, Brown, called for citizens let their lawn turn brown, many people did more than just comply; it instigated a citizen-led public shaming on Twitter with the hashtag "droughtshaming" of those who did not do so: a sign that water conservation is becoming the norm[232]. The state was actively encouraging this norm-shaping, by eventually making the call mandatory by installing fines for lawn watering and other water use defined as "wasteful" of up to $500, and setting up a government website where people could report violations (or as it was more popularly referred to: "snitch on water wasters"[233]).

California released a new, ambitious holistic water conservation framework in the summer of 2024[234]. While this framework is aimed at water infrastructure, especially water utilities, rather than citizens and other end-users, its name still makes clear the government's intent of cultural change around water use: "Making Conservation a California Way of Life". Water utilities will have to improve their efficiency by as much as 30% in some cases in just 16 years. A cultural shift to align everyone in the state with this ambitious goal is indeed necessary, but it could be achievable judged on California's track record. A 2017 survey conducted in the state showed that a majority of citizens believed it their civic duty to conserve water[235], and the water reduction goal of 25% that was set during the 2012-2016 drought was achieved[236].

A California freeway during the 2012-2016 drought

227) Wallace (2021)
228) EPA (2024h)
229) EPA (2024i)
230) RainBird (2024)
231) California Water Boards (2024)
232) Milbrandt (2017)
233) Ryan (2014)
234) California Water Boards (2024)
235) Tobin (2017, March)

Empowerment

Complementary to awareness raising, it could be said, is the provision of tools for people to act. The EPA's free Water Technical Assistance (WaterTA) program is a prime example of this. WaterTA was launched in April 2024 and is intended to help communities take initiative to improve their local water infrastructure[237]. It offers webinars and presentation and helps connect communities to experts who can assist with assessment and implementation of solutions for their drinking water, sewage, and stormwater needs. This way, WaterTA supports communities with things like identifying lead pipes for removal, enhancing resilience against cybersecurity threats, identifying climate adaptation strategies, providing resources for workforce development, addressing stormwater challenges, and identifying how to comply with the Clean Water Act (CWA) and the Safe Drinking Water Act (SDWA). WaterTA can also assist with the application process for federal funding for the identified solutions, as part of what was made available through the BIL. One can see how this social incentive is also complementary to the economic one of providing funding, as it enables communities to make the most of this funding.

Another way that government can empower communities to improve their drinking water systems is through regulation on governance of these systems. As mentioned earlier, even a lot of private water systems are not-for-profits, including the about 3,300 water cooperatives in the US. Water cooperatives are small not-for-profit enterprises that are owned by the same people who are using the water, typically located in suburban and rural areas. Research suggests that water cooperatives deliver water with higher quality for a lower price compared to for-profit private water systems[238], a point we will come back to in the Synergies chapter. Water policies can make a significant difference. Studies find that in states with regulations favorable to corporate providers, water utilities charge higher prices[239]. Conversely, regulation conducive to establishing such cooperatives when appropriate and desired, can empower local communities to take affordability and safety of their water commons in their own hands.

Not all water systems will be suited for cooperative governance. The vast majority of Americans get their water from municipal water systems. Even then, awareness on water issues will bring support for certain water policies, including funding proposals, by voting as well as being a vital part of its successful implementation.

Public perceptions

Perceptions on water issues held by the public can be crucial. Apart from exercising their right to vote on related matters, public perceptions can influence what in economics are called "friction costs": the time, energy and money spent executing policies and enforcing regulation. Perceptions of certain water policies' necessity and fairness could influence support and adherence to them, even those impacting people's water bills and daily habits. Trust in tap water quality, for example, might soften the sewage charges on the water bill — as well as reduce the consumption of bottled water and high-sugar sodas, with carry other negative environmental and health impacts[240]. Awareness on the importance of water conservation and how to support that, can be crucial for government-led water conservation efforts to succeed. So, what are the attitudes, trust levels, and willingness to pay and act around water issues in the US?

Concern and confidence

Overall, Americans seem to care about water relatively much. Respondents to a 2021 Gallup survey, for example, were more worried about water quality than other environmental concerns[241]. Over half of the population responded they were "a great deal" concerned with pollution of drinking water (56%) while another quarter reported to be concerned "a fair amount" (24%). A 2021 and another 2022 survey found similarly high shares, almost 7 out of 10, of Americans concerned about water scarcity and droughts[242]. And according to a 2024 poll, concerns among American voters for water affordability and water infrastructure have been steadily rising over the past few years[243].

People hoding hands behind drinking water.

237) EPA (2024j)
238) University of Wisconsin Center for Cooperatives (n.d.)
239) Zhang et al. (2022)
240) Rosinger et al. (2021)
241) Brenan (2021)
242) American Water (2021), Martinez (2022)
243) US Water Alliance (2024)

Given the variety in outcomes across the US when it comes to water quality and price, it's probably not surprising that public perceptions on water-related issues are influenced by factors such as location, race, and age. Political affiliation, educational level, and exposure to drought and water contamination, are also factors in shaping confidence in water quality and trust in organizations responsible for water management. For example, there is a positive correlation between level of education and reported concern about water-related issues[244]. Although democrats are generally more concerned than Republicans about environmental issues, including water-related ones, a bipartisan majority (65%) supports federal investment in water infrastructure, even after the BIL will sunset[245]. Communities that have suffered droughts and/or water quality issues are more likely to rate this environmental problem as important and report elevated levels of concern[246]. But national news stories can also have an impact. For example, after the Flint, Michigan crisis, Americans in general became more aware of water quality issues[247]. Public confidence in tap water is especially low amongst disadvantaged groups, 84% of which were found in one survey to have no significant confidence in drinking water [248]. Lack of such confidence can lead to "tap water avoidance", and indeed, 10% of white Americans surveyed in another study reported not drinking their tap water, while 20% to 30% Black and Hispanic Americans reported the same[249].

Trust and politics

In general, trust in water utilities is at an all-time low[250], and the majority of Americans also find government and business not taking sufficient responsibility for sustainable water management[251]. This does not necessarily mean there is also no trust that things can be improved. Although survey respondents lamented lack of action on water issues from government and business, most Americans respond unfavorably to the idea of less federal regulation[252], while a strong majority of 70% remained optimistic that these issues could be effectively addressed by them[253]. Indeed, in one study, the highest support for government intervention to improve the tap water quality was found in the lower-income groups[254]. This translates into voting behavior: 63% of all voters in one 2024 poll responded they'd view an elected official who supported additional investment in water infrastructure more favorably, against 14% viewing such an official less favorably[255].

Willingness to act and pay

Apart from what seems then to be a relatively favorable "Overton window" for water policy, the American public also seems willing to take personal action. The large majority, 9 out of 10 respondents to one 2021 survey, reports a willingness to be water conscious by changing daily habits[256]. The vast majority would describe themselves as very or at least somewhat water conserving, contrasted to 9% from that study reporting to not conserve at all[257]. At the same time, when tested on some basic water facts, it becomes clear that most Americans are illiterate on water issues like embedded water footprints and ways to conserve[258]. In fact, this is confirmed by 40% of respondents themselves in one study, who say they don't know enough to conserve water. This is why, as mentioned earlier, awareness campaigns should not just focus on urgency, but also knowledge building and clarification such as through certifications.

Americans seem willing to put their money where their mouth is too. Many studies indicate a willingness to pay by Americans for watershed restoration and preservation of water ecosystem services[259]. When it comes to infrastructure specifically, a large portion of Americans worry about that too, and are willing to pay for improvements[260]. The US Water Alliance, which polls Americans every year on water issues, found in their 2024 survey that a majority of voters (61%) would accept moderately higher water rates to support local utility projects that improve water accessibility and community health[261].

When confidence in tap water quality is low, people switch to bottled water for daily consumption.

244) Garcia-Cuerva et al. (2016)
245) US Water Alliance (2024)
246) Tobin (2017, March)
247) David & Hughes (2024)
248) Tobin (2017, June)
249) Rosinger et al. (2021)
250) David & Hughes (2024)
251) Kennedy (2023)
252) Tobin (2017, June)
253) Martinez (2022)
254) Tobin (2017, June)
255) US Water Alliance (2024)
256) American Water (2021)
257) Warner et al. (2017)

Connecting

Lastly, let's have a look at some of the wider social systems, and in this case, also some of the temporal and distributive aspects around costs and the way these can shape economic incentives. One of the wider systems is obviously the overall government budgets, as well as the economy as a whole. The federal and state funding assistance provided to water systems and/or water users, for example, come from taxes, which are paid by the same parties that use water: citizens and companies. Yet, indirectly these could help to alleviate other financial burdens on the demand side, such as from water prices (a distributive aspect) or longer-term increased maintenance for infrastructure; short-term savings on maintenance very often come back in higher costs for replacement in the medium term (a temporal aspect). The city of Baltimore may not be known for a water crisis, but it is one of many examples of this. Because of an average of 1,000 pipe breaks every year by now, it sees over half its water budget consumed by infrastructure repairs and replacements(262). On the other hand, there are also wider (and longer-term) economic benefits to be expected; the US Water Alliance estimates that fully funding the US' water infrastructure could deliver a $4.5 trillion gain in GDP, a $2,000 annual increase in household earnings, and create 800,000 new jobs(263).

Other financial impacts are (even) harder to estimate, such as lost workforce productivity, and avoided health care costs, legal fees, and environmental cleanup costs. Especially when combining the costs to society — even while still leaving out the non-quantifiable impacts on quality of life — these can be significant and over the medium term outsize short term funding costs by orders of magnitude. To come back to the well-known example of Flint: The switch in water source was budgeted to save $5 million; the resulting water crisis has cost the state of Michigan $600 million in settlements with residents alone(264). Water rates have shot up for residents, who also spend significant part of their disposable income on bottled water(265). $87 million was spent between 2017 and 2020 for pipes replacements, and the medical debt that has been accrued by Flint households by now is considered such a crisis that in October 2024, the city voted to erase $32 million of it(266).

Overall, the US is already incurring the cost of outdated repairs, inadequate response to climate change, and unsustainable water use in terms of overconsumption and the extent to which it's being polluted. Experts have warned, for example, that failure to carry out the necessary infrastructure repairs might make water-borne diseases more prevalent(267). This could ultimately also affect the price of health insurance and medical treatment, meaning this would have financial impacts on the overall government budget too. For good measure, water-borne diseases in the US infect about 7.15 million people annually, leading to around 6,630 deaths, 601,000 emergency department visits, and 118,000 patient hospitalizations, costing an estimated total of US $3.33 billion(268). Climate change is already exacerbating extreme weather events like hurricanes, heat, drought, and floodings. Floodings alone have cost the US a total of $850 billion(269) since 2000. Extreme heat events are expected to reduce the number of working hours per day by 2%(270) and based on empirical data from the State of Virginia are estimated to already costs the US more than $1 billion each year in emergency department visits ($177.3 million) and hospital admissions ($834.9 million)(271). In 2023, about 2.3 million Americans were displaced because of extreme weather events(272), which combined since the 1980's has cost the US a cumulative amount of $2.7 trillion(273).

Francis Scott Key Bridge over Patapsco River and outer Baltimore Harbor, Maryland.

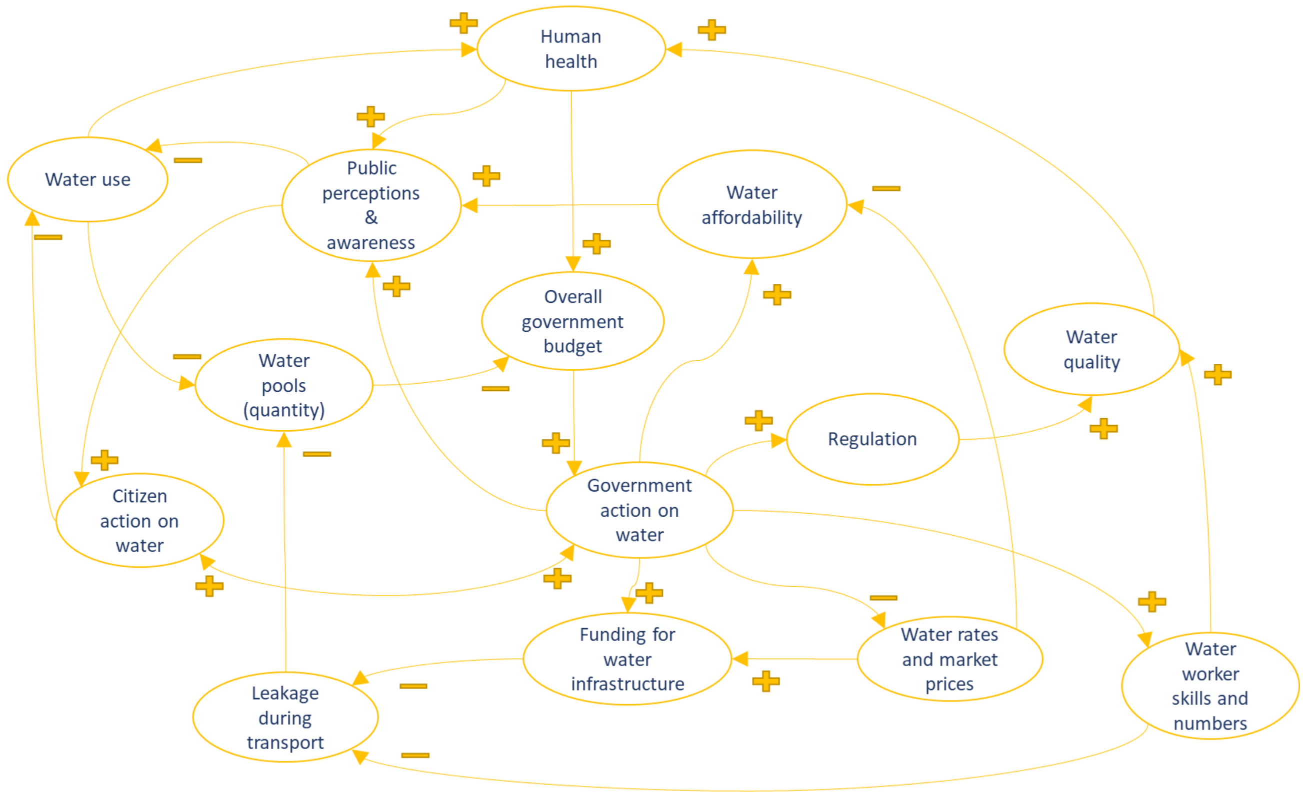
262) Mills (2023)
263) Value of Water Campaign (2024)
264) Vespa et al (2024)
265) Fonger (2015)
266) Jeltema (2024)
267) Mills (2023)
268) Collier et al (2021)
269) Flood Defenders (n.d.)
270) Lehr & Pela (2024)
271) Woolf et al. (2023)
272) Wachtendorf & Kendra (2024, March)
273) Smith (2024)

On the other hand, the more slow-drip impact of water stress and insecurity are significant too, estimated at $8.58 billion in productivity and labor loss, reduced household earnings, and higher healthcare costs every year(274). Overall, it is estimated that every person born in 2024 will bear an expense of half a million dollars over their lifetime because of climate-change induced cost increases in housing, food, and water prices, and higher taxes(275).

Most Americans do not live with such numbers in their head. But while the above-described interactions are often indirect and diffuse, voters are somewhat aware of them. As we saw, Americans care and worry about water issues relatively much, and there is a growing sense of urgency and consensus that water infrastructure in the US is lacking and that additional investments are needed to improve the situation – investments citizens are willing to support through voting and paying higher water prices. These notions are part of the overall culture in American society. Surveys show that overall, there are shifts in public attitudes discernable towards greater awareness and worry about things like water scarcity, as well as economic and social inequalities (276). Americans also realize more and more that these issues are interrelated, within countries and geopolitically(277). The younger generations in particular feel strongly about these issues(278).

The connections between the main social aspects discussed in this chapter are depicted in the CLD below. With all three lenses now complete, we are ready to dive into the analysis.

Exhibit 30. Causal Loop Diagram (CLD) of social interactions.



274) O'Neill (2023)
275) Nova (2024)
276) Gallup (2024), Horowitz et al. (2020)
277) European Investment Bank (2023)
278) Tyson et al. (2021)

Chapter 3. Synergies

To resolve the issues of US water infrastructure independently would be a futile attempt. As evidenced, environmental, technical, and social elements interact continuously. Throughout this report, we've hinted at their synergistic relationships. In this chapter, we analyze these by putting the CLDs together, revealing the interdependency between spheres and allowing for identification of a holistic set of solutions that use interactions between environmental, social, and technical aspects to mutual benefit.

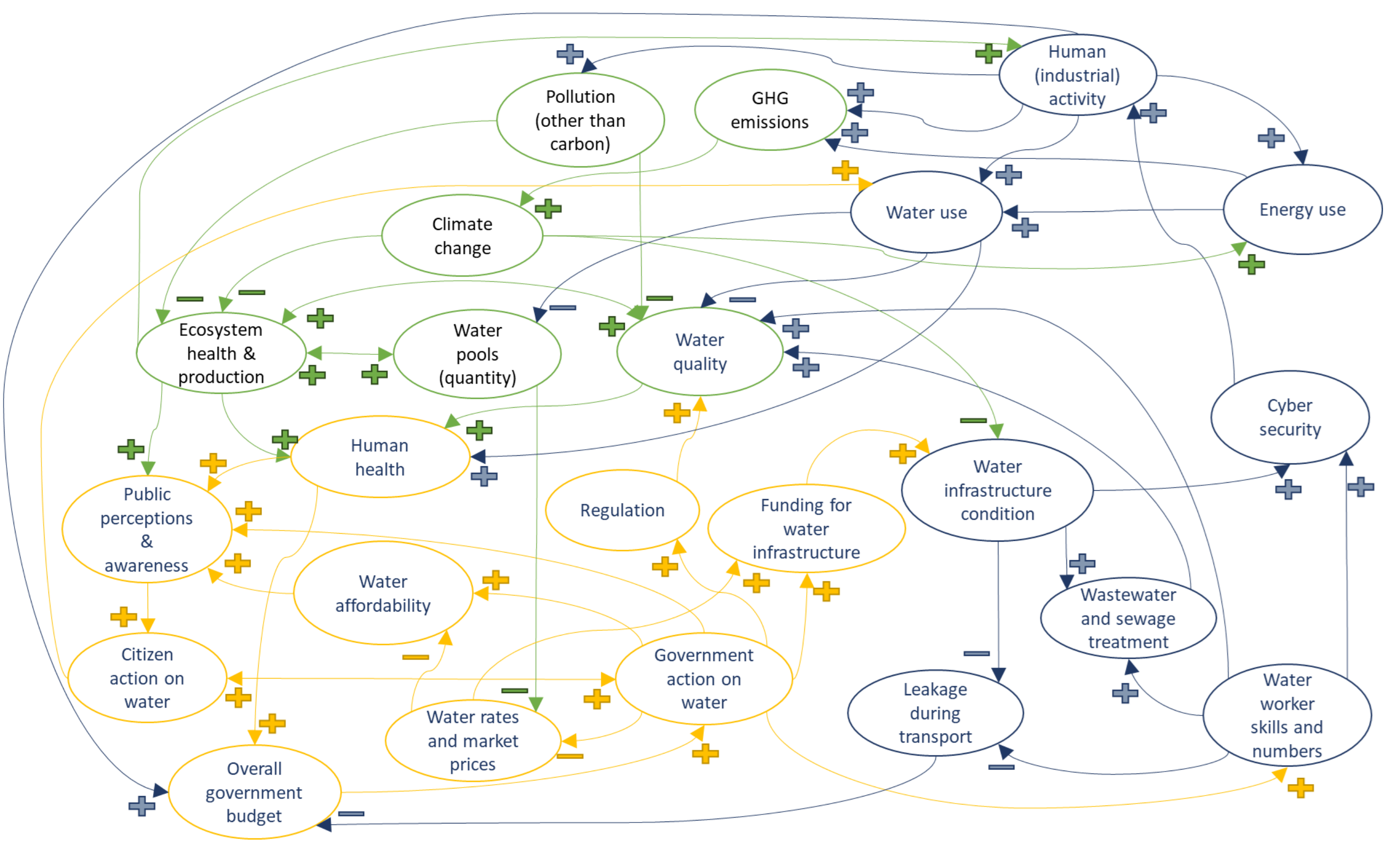
Analysis & discussion

So far, each lens has had its own CLD. The reader might have noticed duplicates amongst them, such as *Climate change* or *Water quality*. Funding was a somewhat disconnected factor in the technical lens CLD, but got more connections in the social one. This is, of course, because the boundaries of the lenses are diffuse, and many interconnections between these exist. If that's the case, then it should be possible to connect the different CLDs to form an extended one. Based on the outlines in earlier chapters and this merged CLD, we can then analyze if there are any interactions in particular that might be of interest.

Merging the CLDs

Exhibit 31 shows a merging of the CLDs for an overview of all interconnections relevant for this analysis[279]. From here, we can see if anything stands out, be it a single factor or a group. For example, one factor might be especially connected in some way, making it a particularly relevant as an influence on other parts of the system, or conversely, particularly influenced by other parts. A group of factors might form a nexus: a part of the CLD that works as a large (either desired or undesired) positive loop. Or, on the other hand, a group might stand out for what seems to be a missing connection or two in what could otherwise be a desired reinforcing nexus.

Exhibit 31. Combined CLD of environmental, technical, and social interactions.



279) This means that some of the environmental factors and connections have been removed, because as explained in the following paragraph, these Earth systems parts cannot be influenced. Specifically, the factors of Evaporation, Precipitation, Surface runoff, and Land-use change have been removed. The total US infrastructure condition factor has been removed as well for clarity, as it turned out to not be relevant for the analysis and solutions pertain to the water space.

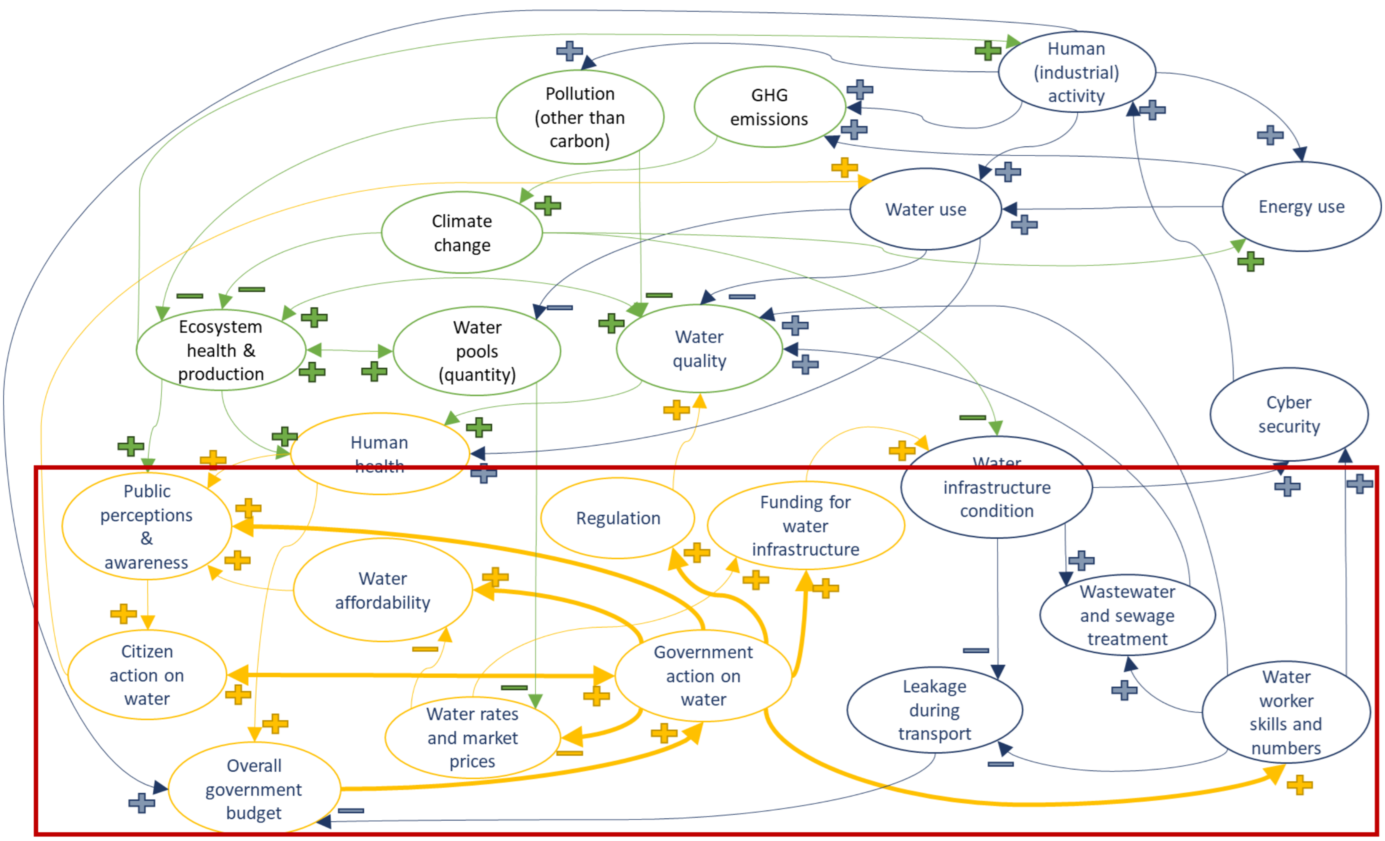
Based on those areas of interests in the CLD, we will analyze in what ways these can be leveraged, if at all. The following three sections focus on government, industry, and citizens as actors in this regard. That's because the behavior of these actors is to some extent within society's control. Not on an individual level — any one person at the very most has some very dispersed influence. But there is some power nonetheless for those actors as a group, where in contrast, many environmental and some technical aspects are completely out of our hands. We would like infrastructure to depreciate much less fast, for example, but humans cannot change the second law of thermodynamics (entropy). Similarly, we cannot change the fact that rising GHG cause climate change. However, as a society we can control how much polluting gases we emit. Based on this fact and characteristics of the CLD, we will now analyze areas of opportunities for a way forward for US water infrastructure, starting with the most connected actor: government.

Government's central influence

Government action on water stands out as one of the factors with the most outgoing connections. It's not the only one with many outgoing connections: so do *Human (industrial) activity* and *Ecosystem health & production*. We will come back to these two factors in a later section. Factors *Water quality* and *Public perceptions & awareness* also have a relatively high number of connections, however, most of those are incoming, not outgoing. In other words, they are influenced more than they are influential in the system. Government action is decided upon and executed by humans, making it not just influential because of its connections, but possibly a leverage point. Through infrastructure funding and regulation, for example, it can influence these other highly connected factors. As we saw in earlier sections, upgrades and maintenance to infrastructure made possible through funding will improve water quality, as will regulation on water quality standards and polluting activities, thus influencing these factors indirectly.

These and all other connections are highlighted in pink in Exhibit 32. It's worth noting that most of these are outgoing, but there are two going in, from *Overall government budget* and *Citizen action on water*. So, if it's understood that things like funding for water infrastructure, water regulation, governing on water affordability, and investment in water workers are important for US water infrastructure (which we hope by now is the case), it could be worth exploring if these two incoming connections can be strengthened and/or if the factors which the outgoing connections point towards can be supported through other means.

Exhibit 32. CLD with connections to Government action on water highlighted in pink.

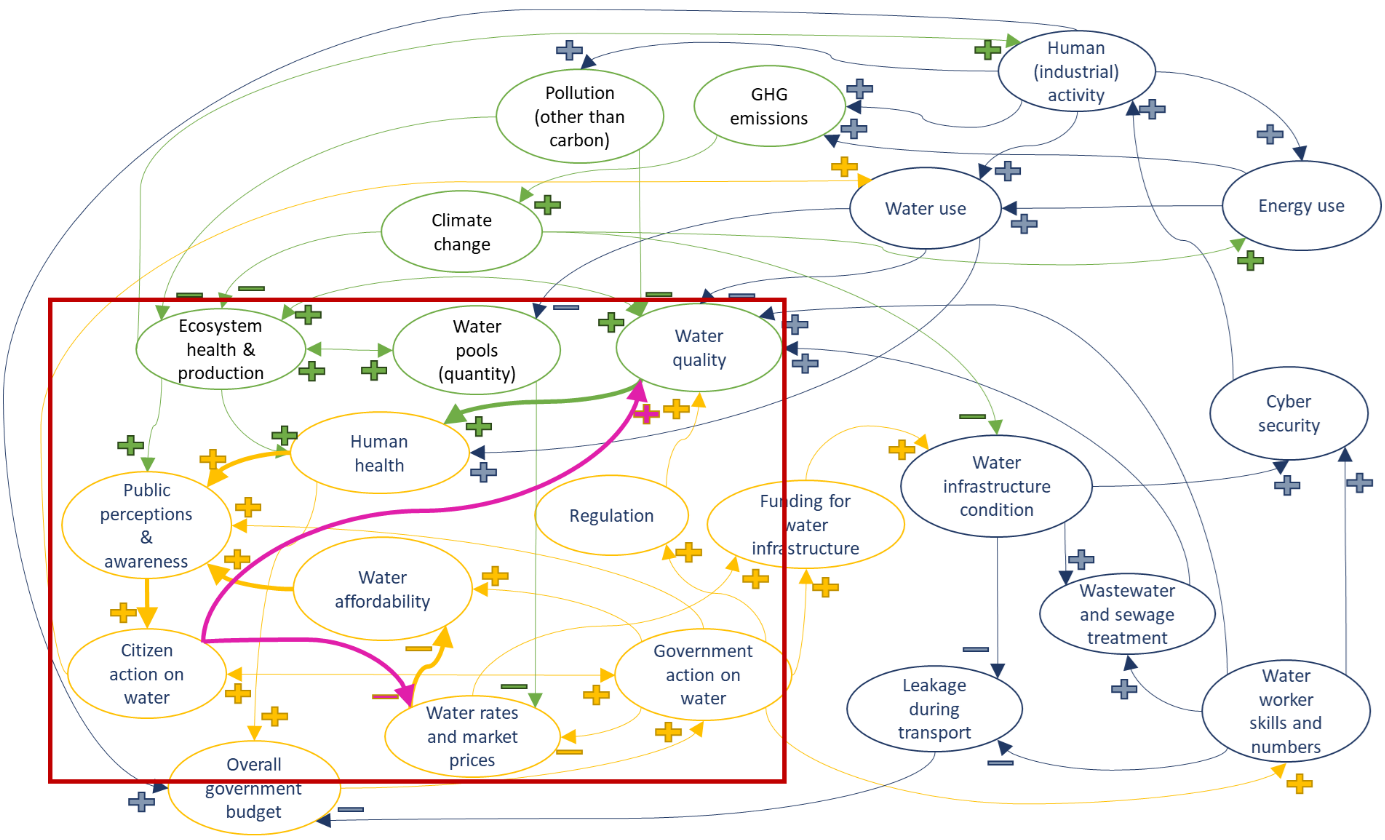


Citizen's underused influence

In contrast to *Government action on water*, a factor that is relatively sparsely connected is the *Citizen action on water*. It has only three connections, which seems few given the focus of this CLD (even though one of the connections is bidirectional). Yet, this is an unsurprising outcome from literature that mostly focusses on government and secondly, industry, as a water player. Citizens are mentioned amply, but mostly as consumers, i.e., water users and payers, and to a smaller extent as voters. That's why the two outgoing connections are to *Water use* and *Government action on water*. There is, for example, the reinforcing feedback loop of *Government action on water*, *Public perceptions & awareness* and *Citizen action on water*. This is a well-known dynamic, which can be beneficial (as in this case for water awareness) or toxic (as in the more general case of propaganda).

It is worth analyzing if we can find some newer insights from the research on citizens as more active players. These might allow for some connections to be strengthened and/or added. In fact, we had mentioned one such phenomenon: water cooperatives. Without going into the details of these here, the overarching principle is that citizens manage their local water commons themselves. They play a threefold role as users, managers, and suppliers. Empirical data shows that water cooperatives deliver water with higher quality for comparatively lower prices. Such initiatives then, would add connections to water quality and water rates as highlighted in Exhibit 33. The extra connection supporting *Water rates and markets* takes some of the pressure off *Government action on water,* identified as desirable in the previous section. The plus between *Public perceptions & awareness* and *Citizen action on water,* the minus between *Citizen action on water* and *Water rates and markets*, the minus between *Water rates and markets* and *Water affordability*, and the plus between *Water affordability* and *Public perceptions & awareness* together form a desirable reinforcing feedback loop (two minuses that cancel one another out and two plusses) which could be called a "Community confidence building" loop. And with the added link to *Water quality*, there is now what we could call the "Water Quality Communization" loop: a desirable positive loop (plusses only) between *Water quality, Human health*, *Public perceptions & awareness* and *Citizen action on water*. Because the two loops are overlapping, we cold also call there combination a "Water commons empowerment" nexus.

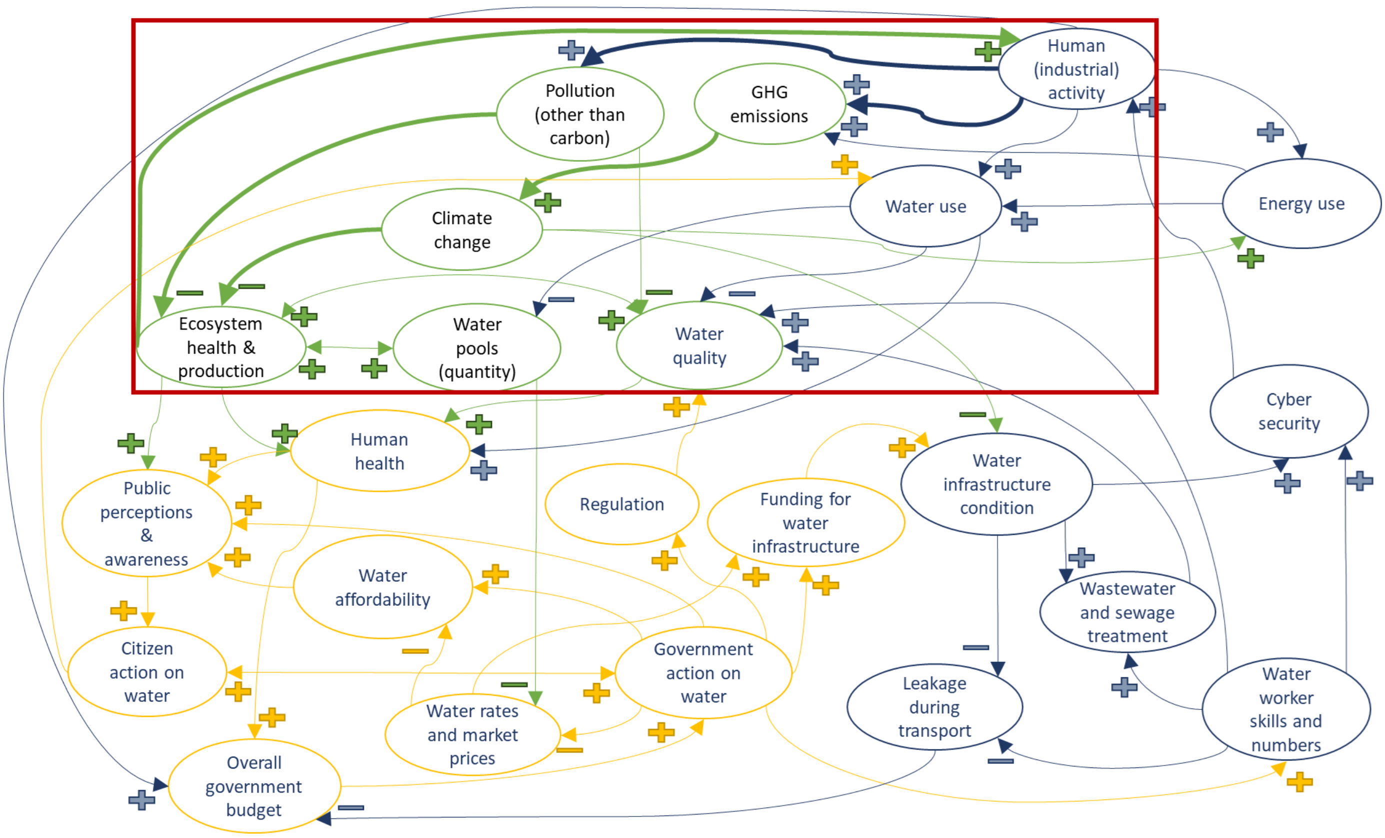
Exhibit 33. CLD with added connections for citizen action highlighted in pink, forming the Water commons empowerment nexus.



Working for nature

Let's come back the other highly connected factors, *Human (industrial) activity* and *Ecosystem health & production*. Both have relatively many outgoing connections, but there seems to be a difference: *Ecosystems health & production* has outgoing positive connections to things like *Human health, Water quantity*, *Human (industrial) activity*, and *Water quantity*, illustrating how ecosystem health supports many other vital aspects of society. *Human (industrial) activity* seems to have more undesired effects among its positive impacts. Two of the connections going into *Ecosystem health & production* have a negative (and in this case also undesired) impact: climate change and other pollution, which both come from *Human (industrial) activity*. This leads to undesired negative loops, as highlighted in below Exhibit 34. The plus from *Ecosystem health & production* to *Human (industrial) activity,* the plus from *Human (industrial) activity* to *GHG emissions*, the plus from *GHG emissions* to *Climate change*, and the minus from *Climate change* back to *Ecosystem health & production* together form a negative loop (three plusses and one minus constitute a negative feedback loop). The same goes for the loop of *Ecosystem health & production*, *Human (industrial) activity,* and *Pollution (other than carbon)*. Since these loops are overlapping too, we could refer to them together as the "Unsustainable" nexus. Given that all of society, and thus also the whole of the economy, reside in ecosystems, it would be worth exploring whether some connections from the societal and technical factors could be beneficial. (As mentioned earlier, we typically do not have any influence on how environmental factors interact.) We can't draw connections just anywhere between these factors either; they have to exist already and be able to be strengthened by human actors, or, they'd at least have to be possible even if currently not much in existence. The logical social and technical factors to consider, then, are the ones capturing innovative ways by citizens, government, and industry for regeneration: minimizing damage as much as possible, and then restoring more than what damaging impact was unavoidable. With regards to this "innovation for nature", we'll focus on the role that human (industrial) activity can play. Government and citizen action can spur innovation as well — and certainly the US government has been a major innovating force for many decades[280]. But in this sense, their role is similar to the innovative role for industry we'll describe next.

Exhibit 34. Negative feedback loops, or the Unsustainable nexus, highlighted.

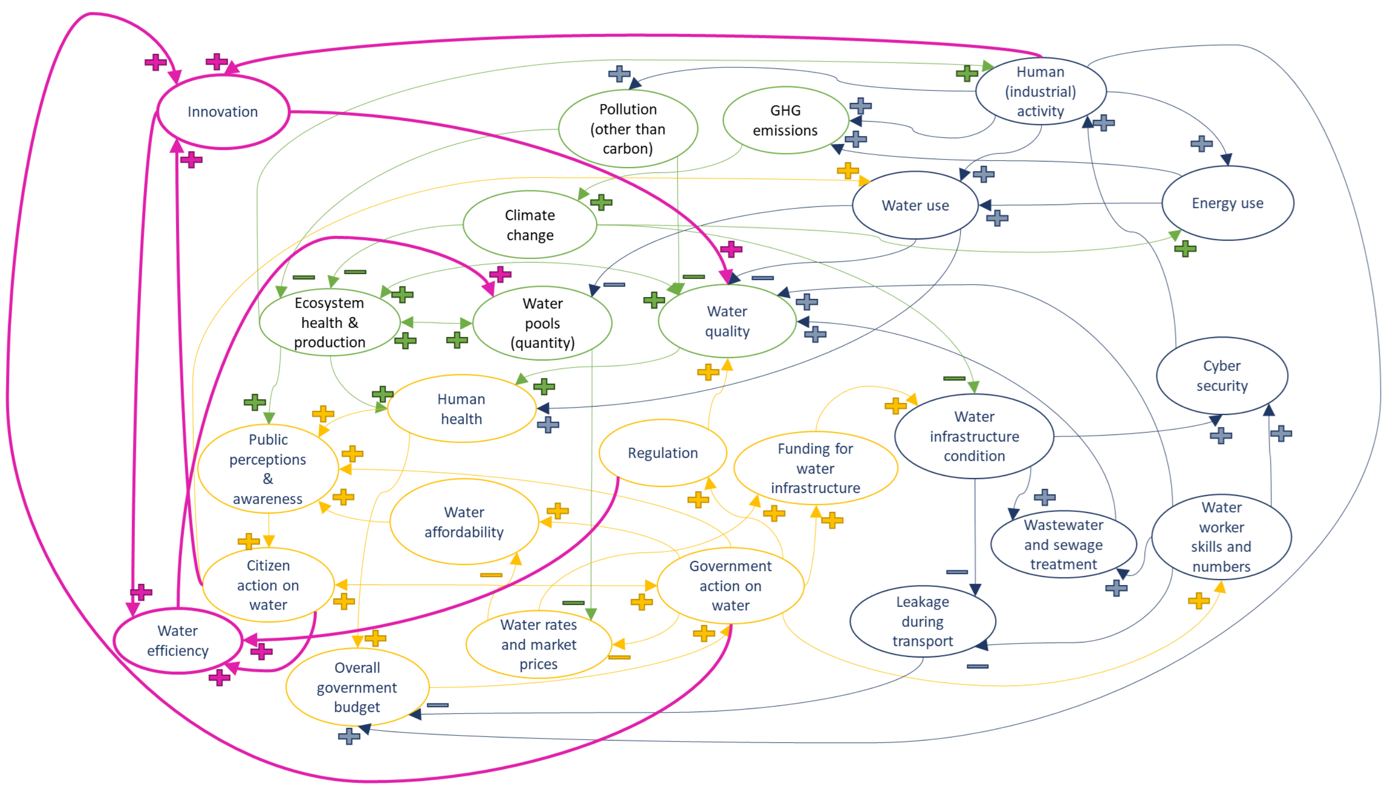


280) Mazzucato (2011)

When it comes to industrial activity, the CLDs might have been considered a bit unfair. *Human (industrial) activity* has many outgoing negative connections, but the industry is also a driver of innovation. Although this does not happen automatically, such innovations can be used to environmental benefit. On the topic of this document, new technologies that improve water efficiency and track water use can improve water availability (*Water pools (quantity)*). And new technologies for wastewater treatment can improve *Water quality*. We can add a factor *Innovation* and *Water efficiency,* and connect it to these existing factors in the CLD. This could be strengthened by another connection to *Water efficiency* from *Regulation* (via *Government action*), indicating a move towards setting up and enforcing efficiency regulation instead of only certification standards. In addition to citizen action as described in the previous section, citizens can further act as a market force when it comes to strengthen their preference for water efficient products, something which they have been doing already, as discussed in the previous chapter. Exhibit 35 shows the CLD with all these changes highlighted.

The reason these factors and connections were not already in the CLD is that they are comparatively weak. Not all connections can be drawn in a CLD, this would make it too overwhelming and analysis impossible. Despite innovations, government action, and citizen activism, GHGs and other pollution are still growing, meaning they are stronger than mitigating impacts from innovation. This does not have to be the case, however. The connections from *Innovation* to *Water quality* and *Water efficiency* could be strengthened. Then, two desired positive feedback loops would appear for water quality (*Innovation, Water quality, Ecosystem health & production*, and *Human (industrial) activity*) and water quantity (*Innovation, Water efficiency, Water pools (quantity), Ecosystem health & production*, and *Human (industrial) activity)*. Climate change and other pollution are still there, but there are now balancing forces added. This combined with the added regulation from government and citizen action on affordability and quality has given rise to more positive feedback loops. There are now also two reinforcing loops for water quality and quantity for government regulation. The one on water quality (*Government action, Regulation, Water quality, Human health,* and *Public perceptions & awareness*) already existed but could use strengthening, and the one on quantity (*Government action, Regulation, Water efficiency, Water pools (quantity), Human health*, and *Public perceptions & awareness*) is new. Similarly, there are two desired reinforcing innovation loops for government for both water quantity and quality, running through *Innovation*

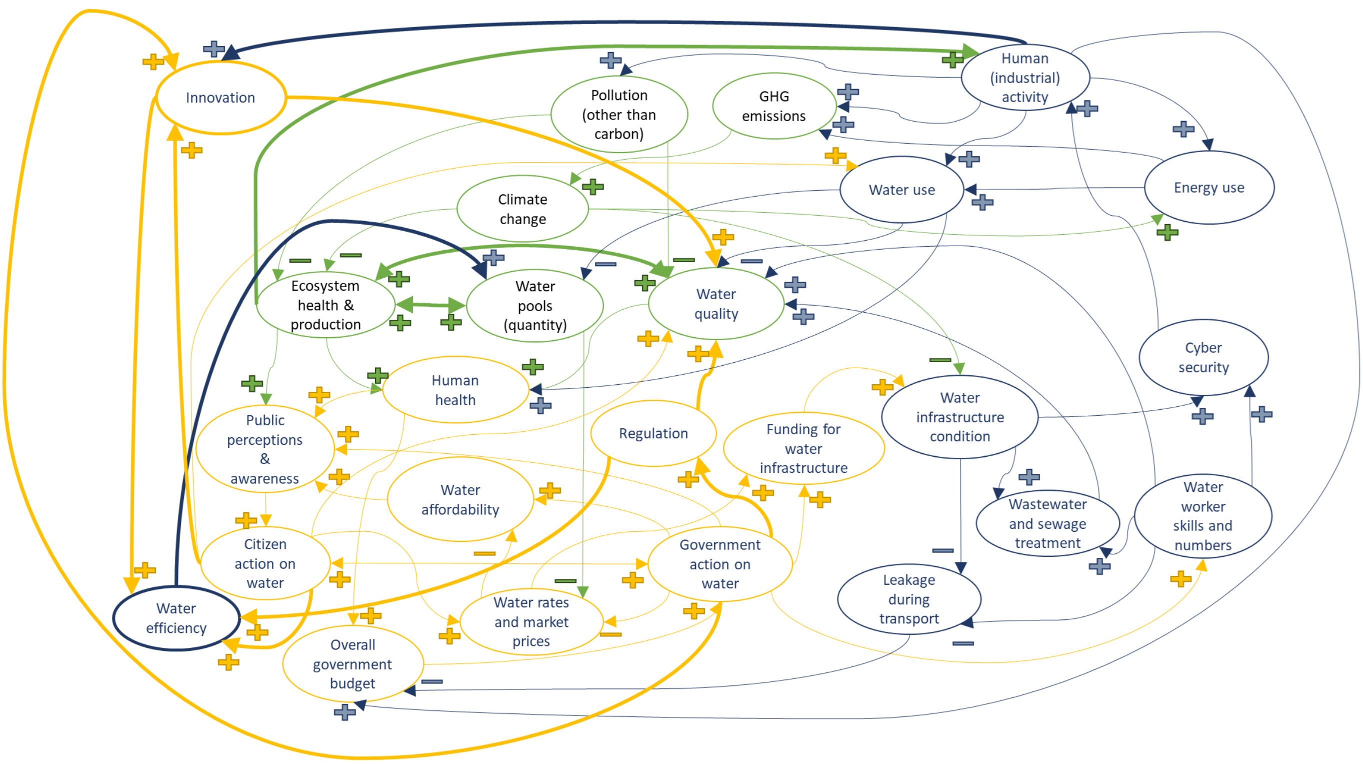
Exhibit 35. CLD with added connections to innovation for water quality and quantity from all water players highlighted.



instead of the *Regulation* factor. And similarly, two such positive feedback loops now exist for citizen action: through *Human health, Public perceptions & awareness, Innovation, Citizen action on water* and then either *Water quality*, or *Water efficiency* and *Water pools (quantity)*.

All the described new connections are positive ones, meaning they would constitute a reinforcing nexus. If it is strong enough, the system could transform towards something where the indicated desired positive feedback loops together outweigh the undesired ones that are present. Such a "Regeneration" nexus is highlighted in the new CLD in Exhibit 36. Because of the critical role of water affordability in sustainability, the feedback loop for citizen action on affordability, identified in the previous section, is also included in this CLD (but not highlighted in the nexus). This new CLD shows more connections between social, technical, and environmental aspects, suggesting a more integrated and thus better-functioning business, societal, and eco-system. It also shows more balance, despite the by now admittedly cluttered connections; there is action from all stakeholders, not just predominantly from government, and the action is on both water quality and quantity. It should be noted that the changes described above would have to be a deliberate choice by people, hence this section's title: a working for, not just with (and certainly not against), nature. Now that these principles have been identified, we can move on to discussing concrete realizations of what such dynamics can look like.

Exhibit 36. Updated CLD with regenerative human impact on water highlighted.



Solutions

This last part of the chapter should not be interpreted as an exhaustive list of the best practices for "solving" the issues in the US water infrastructure. They are mentioned as examples of the synergies identified in the first part of this chapter, and indeed in this document so far. They were selected because of their promise as concrete practices in two complementary ways: they are already existing and not purely untested theories, while also not being so mainstream and commonly understood that mentioning them is redundant. The first way is supported with real-life examples in each section. The second way by a short description of how the solution is embedded in the newest developments within the broader scientific and business community. The solutions covered here are: tiered water rates, nature-based solutions, digital solutions, innovative funding instruments, and last but not least: cooperation.

Tiered water rates

Tiered water rates are perhaps the most obvious solution after having gone through the analysis. When properly designed — as discussed, this is an important condition — such pricing schemes can alleviate some work for governments. In the merged CLD in Exhibit 31, water rates help provide some of the crucial funding for infrastructure, but the government must also engage in water affordability programs to compensate low-income households for these higher prices. As discussed in the social lens, the right design in tiered rates accomplishes the two goals at the same time, by virtue of optimal distribution of infrastructure costs: "water wasters" pay relatively much for water use, while commercial and residential users that stay within their needs-based allocation pay comparatively little. This way, the undesired reinforcing feedback loop discussed in this paper of bad infrastructure condition and rising water rates, can be inverted into a desired one: the higher revenue from heavy water users can be applied to infrastructure upgrades, which reduces non-revenue water losses due to leakage and breaks, and improves the quality of the transported water for everyone. The Irvine Ranch Water District in San Diego, California, for example, uses five "blocks", with the highest block costing a water users eight times more than the lowest one[281]. This way, customers who consumed less water, are subsidized by the higher prices charged at higher tiers. This pricing mechanism is credited for the Irvine Ranch Water District achieving a 37% conservation rate.

While best practices in the tier design are a topic of ongoing discussion, tiered pricing in general is considered the most effective strategy for managing water demand in a way that balances financial, environmental, and social sustainability (i.e., solvent and well-functioning water systems, and water availability, quality and affordability, respectively). The adoption rate varies widely across states, but in the regularly drought-stricken state of California, two thirds of water systems now use some form of tiered water pricing[282].

AI rendition of "water tiers".

281) Equinox Center (2009)
282) Riverside (2018)

Sufficiency and water consumption corridors

This principle of fair distribution of costs based on human needs and environmental sustainability falls in the general trend of rising popularity of concepts like "wellbeing economics"[283], or as it is termed more commonly in Europe, "sufficiency"[284]. Both these and some other related terms stand for a development in sustainability research that places human needs and ecological limits at the heart of society, including its economy. Although not a mainstream concept (yet), it's worth noting that most water systems already operate with principles of sufficiency. The most triggering – although equally fast gaining in popularity – of the terms in this line of thinking is degrowth[285], which views growth more selectively by asking questions such as "what is our optimal size against the criterium of their societal purpose?". As mentioned in the social lens, water municipalities have already answered this question in many cases and decided that their goal is not to grow any further, but rather to reach or maintain a steady state of financial, operational, and environmental sustainability.

Concrete policy proposals in this sufficiency thinking include consumption corridors: lower and upper limits for consumption based on human needs (the lower limit) and planetary boundaries (the upper limit). Tiered pricing is designed in a similar way: the low tiers allow for access to water above a needs-based lower limit. Disproportionately higher prices indicates that the upper limit is approaching or has been crossed. The right tiering design then, serves as a strong incentive to stay within one's "water consumption corridor". In this sense, tiered water rates do not just make sense as a desired dynamic in our CLD but are also well-embedded in general developments of sustainability research.

Nature-based solutions

Nature-based solutions (NBS) in general are sustainable practices that use natural processes and features to address environmental, social, and economic challenges[286]. For water, NBS can help improve water quality and security by, among other things, aid in flood water and rainwater management, mitigate climate risks, improve water absorption, storage and filtration, and overall water stocks replenishment. They are typically implemented by private or public entities and generate benefits for these players and citizens in general. Thus, NBS are examples of what practices in the Regeneration nexus look like. In addition, they may reduce negative impacts on the overall government budget, because of the social benefits that they produce.

Permeable pavement (up), green roofs in Chicago (top right), and a living wall (bottom right).

NBS comprise an array of possibilities, from small to system wide. Small examples include permeable pavement, consisting of vegetation, rocks, and pebbles, which helps manage stormwater runoff by boosting infiltration back into the ground. NBS can look like rain gardens, plant boxes, and other nature-based infiltration practices that augment water storages[287]. Green roofs, although they don't help with infiltration, capture rainwater and thus also aid in rainwater run-off management. They also serve as home insulation, thus supporting indoor climate control. Similarly, "living walls", the vertical equivalent of green roofs, can capture rainwater (depending on their placement), provide insulation, and when implemented at a larger scale, help manage local humidity.

283) Hayden (2024)
284) European Commission (2023)
285) The New York times (2024)
286) Choi et al. (2023)
287) EPA (2024, April)

Larger-scale examples of NBS include small wetland restoration and construction of parks, especially waterfront parks, which also support rainwater absorption, storage, transmission, and infiltration, ultimately increasing water availability(288). On this large scale, such an NBS also supports flood management – hence the often waterfront location – by minimizing the risk of overland flow during heavy rainfall and extreme weather events. (Of course, parks in general provide this function of flood control through water absorption, but the waterfront ones have become more pertinent because of the increased risk of waterways overflow due to climate change.) Tree planting and other vegetation on a larger scale also bring benefits of humidity control, especially throughout urban centers, as well as a host of other health and social benefits like improved air quality, summer shade, and recreational opportunities for residents(289). This is where one starts to talk about NBS as "green infrastructure": the combination of NBS like permeable pavements, rain harvesting systems, green garden rooftops, integrated synergistically with both environmental infrastructure like a river or wetlands and physical technical infrastructure like conveyance instruments (pipes and sewers).

New York City (NYC) has been showcasing this since the 1990's, by adopting a series of green infrastructure solutions to improve its water quality, water security, and resiliency to climate-change risks. By integrating NBS like rain gardens, green roofs, and constructed wetlands into conventional grey infrastructure, water retention from evaporation and precipitation in the "concrete jungle" has significantly increased(290). The Big Apple's green infrastructure is credited with improved stormwater capture and thus less runoff. Because of the resulting reduction in water pollution, NYC has reportedly saved over $300 million annually and avoided having to construct an additional $8 billion wastewater treatment plant. This is not unique to NYC; green infrastructure is regularly proving to be more cost-effective than grey infrastructure alone(291).

This is especially true when additional benefits are taken into account, such as thermal and humidity regulation and (although often harder to measure) economic, social, and environmental benefits such as job creation, improved citizen health, and less degraded water to treat (thus also improving health because less toxic chemicals are necessary to the treat water). For this reason, NBS and especially green infrastructure reduce the pressure on the Overall government budget factor, one of the two factors we identified as going into the highly influential Government action on water factor and therefore could use some support. Speaking of economics: NYCs green (water) infrastructure has been partially financed through water rates and the government budget – the well-known funding sources – but also used a little less traditional financing instruments like a Payment for Ecosystem Service (PES) scheme. We will come back to PES schemes and other alternative funding instruments in a later solution section.

On an even larger scale there is active restoration of living environments and entire ecosystems, including major wetland areas. Apart from the even bigger impacts in water quality improvement and security, by virtue of restoring the natural filtering processes of the water cycle, there are additional benefits like wildlife habitat forming and global biodiversity in general. Larger scale NBS can also involve more deliberate restoration of the water cycle, such as the strategic and extensive practice of replenishing aquifers. In this NBS, harvested rainwater or treated wastewater is injected directly back into empty aquifers, to both store the harvested rainwater and restore local natural systems. Areas prone to drought particularly benefit from such increased water storage capacity, which can be drawn upon during months of scarcity. For this reason, this NBS is increasingly discussed in the water-stressed US Southwest, because apart from the negative impacts on water quality from rainwater runoff, rainwater harvesting is considered an important – if not indispensable – way to become water neutral (i.e., water independent or net-zero water)(292).

High Line Park in New York City, New York.

288) UNESCO World Water Assessment Programme (2018)
289) Zhang & Qian (2024)
290) UNESCO World Water Assessment Programme (2018)
291) UNESCO World Water Assessment Programme (2018)
292) Crosson et al. (2024)

Circularity and biomimicry

When it comes to using NBS to restore water cycles and ecosystems, we're approaching territory of "Biomimicry" and "Circularity". Biomimicry is an increasingly popular way of designing products, structures, and systems by emulating biological entities and processes[293]. Humans reconstituting the water cycle could be called an attempt at biomimicry. Circularity is an increasingly popular term, and in general refers to zero-waste ambitions – which in practice so far have come down to reductions rather than elimination of virgin materials usage – by reusing, repairing, and recycling products[294]. The circular model is juxtaposed to the linear "take-make-dispose" model by aiming to extend a product's lifecycle as much as possible to keep it circulating in society. For water specifically, this means the ambition of water cycling through society without any permanent losses in quantity or degradation in quality[2945].

Natural systems are circular, so NBS often are part of effective human-designed water circularity programs. The best design could be said to be the one that leaves less water to be managed by people to begin with, as in the case of watershed and ecosystem restorations. Water systems may also adopt NBS to help filter and improve the quality of used water, as discussed shortly. With circularity in general, when the resource or product cannot be restored to as-new condition, it is reused in a different manner. It is the same for water circularity; partially regenerated water may not be suited for human consumption, but in a circular model will be used for things like agriculture, irrigation, industrial uses, flushing of toilets, and firefighting[296].

Amsterdam, a city in the Netherlands, showcases an integrated strategy for circularity of water and other resources. Amsterdam is combining educational programs to raise awareness on the benefits of water reuse with city-wide implementation of such techniques, including NBS like green roofs, but also closed-water systems in buildings by reusing water for other purposes than human consumption. The circularity extends beyond just water to material circularity, by turning sludge into fertilizer to be used in peri-urban or urban farms[297]. In other settings, the sludge can alternatively be used as an energy source, by processing it into biogas. Ultimately, this energy can be repurposed for the facility itself or distributed elsewhere, thus minimizing both water and carbon footprints. Rotterdam, for example, another Dutch city, has focused on water circularity in the health sector specifically. As part of this, the Erasmus University Medical Center and Franciscus Gasthuis General Hospital are filtering medicine residues from wastewater and remnant sludge to create biogas through anaerobic digestion[298].

Another example of biomimicry is the design of a machine that mimics the ecosystem through which water normally cycles. The "living machine" is another NBS example that could be part of the Regeneration nexus in our last CLD. Living machines are based on principles of wetland ecology, integrating microbial communities of up to 100,000 species, macro-bio communities, photosynthetic communities, and nutrient reservoirs[299]. By mimicking the natural flow of wetland ecosystems, the living machine can filter and clean wastewater for reuse in toilets, cooling towers, irrigation, and other similar uses, thereby reducing water withdrawals[230]. There are a variety of living machine types including Lake Restorers, Eco-restorers, and Reedbeds, though the most popular type is constructed wetland environments[231]. The living machine consists of tanks, pumps, automated valves, and a series of small, constructed wetland environments, i.e., wetland cells, positioned in a chain-like fashion. Each cell is a gravel-filled planter that incentivizes the growth of microbial and plant communities that efficiently remove solids and excessive nutrients from wastewater[302].

The living machine at the Port of Portland, Oregon. Creative Commons. Attribution: Living Machine Systems, L3C

293) Biomimicry Institute (2024)
294) Ellen MacArthur Foundation (n.d.)
295) Urrea Vivas (2023)
296) Urrea Vivas (2023)
297) AquaTech (2020)
298) AquaTech (2020)
299) Hung et al. (2014)
300) Living Machine Systems (n.d.)
301) Hung et al. (2014)
302) Living Machine Systems (n.d.)

The living machine imitates tidal wetland cycles, allowing it to efficiently filter, process, and clean wastewater. Living machines are comparatively small, allowing them to be installed indoors and thus in some larger buildings, enabling on-site water reuse[303]. The San Francisco Public Utilities Commission Administration building has an indoor living machine to treat their wastewater, for example. The 13-floor, 277,500 ft2 building treats 5,000 gallons of wastewater per day using this living machine system, which reportedly has reduced its water use by 65%, or the equivalent of 800,000 gallons of water per year[304]. They are also modular, allowing some flexibility in capacity building or reduction when necessary. Operation is relatively easy and maintenance comparatively light; for example, they rarely use harmful levels of chemicals and leakage risks are low[305]. Other reported benefits include attractive exteriors, and good-tasting water at the end of the process. Lastly, living machines typically rely on solar energy for power, thus also minimizing footprints in environmental areas other than water.

It should be noted that experts are clear that for water systems to become in any way circular, a holistic set of changes in water and overall economic regulations and laws are necessary, including more use of the innovative funding instruments (to be discussed soon), establishment of national water-health standards, removing legislation that does not favor nature-based alternatives, legally enforcing water reuse and recycling, establishing more stringent monitoring and disclosure standards for industrial activities, shifting public perceptions on reused water, and creating market demand to adopt these practices[306]. We also saw some of these elements in the examples of circularity in the Netherlands. That said, NBS such as the living machine would make a useful tool within such a holistic approach. Notably, the living machine is not just nature-based; it's a fruitful combination of nature and technology. Because of course, technologies can play a part in regeneration too, as discussed in the next section.

Digital solutions

Digital infrastructure was mentioned in the technical lens. Remote monitoring equipment, smart sensors, digital portals, meter reading technologies, predictive modeling, data analytics, and AI together can be very helpful in improving service reliability and performance of water systems. Digital infrastructure can augment water quality monitoring, increase water efficiency by automating systems and processes, and detect or prevent leakages or other malfunctions through real-time monitoring and predictive maintenance[307]. (It can also detect water theft, but while this is a significant cause of water loss in some countries, this does not seem to be the case in the US.[308]). Tucson, Arizona, for example, implemented AI technology to detect leakages and pipe breaks, where before they would rely on human judgment to identify malfunctions[309]. This reportedly allowed the local water utility to increase their predictive maintenance abilities, reducing both waste and quality degradation of their water. A wastewater utility in San Antonio, Texas, which implemented sensors in its pipes to collect real-time data to optimize the wastewater conveyance network's cleaning schedule, ended up saving thousands of dollars in each location where a sensor was installed[310]. Digital technologies are therefore a good example of innovation that can be part of the Regeneration nexus. These technologies are typically produced by industry, and can be bought both by other businesses and government entities, including municipalities.

Box 4. Smart technologies in a water utility

The water utility Padania Acque used digital and smart technologies to centralize and modernize its operations in the early 2020s[311]. The water utility, which manages water services for 115 municipalities in Northern Italy's province of Cremona, installed sensors in addition to existing water meters to compare data, and integrated all the relevant information of the network in one central system, which was also capable of generating a "digital twin" of the entire network. Predictive modeling software within the system enabled operators to develop a plan to repair and upgrade the infrastructure for leaks. Energy consumption was reportedly reduced by at least 5% and water losses were cut to almost half of the national average, gaining Padania Acque top marks from Italy's national energy and water services regulatory authority.

Water workers are a water utility in Cremona, Italy.

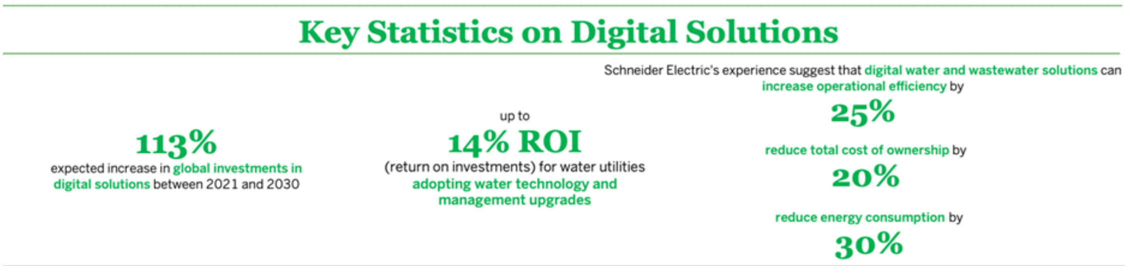
Apart from these technologies' promise to improve service reliability and increase water efficiency and quality, the data collection it facilitates can also enable more forward-looking planning and help fortify the resilience of water infrastructure against climate-change-induced extreme weather events. Some digital infrastructures also allow for online, sharable educational content. This can help water utilities upskill their workforce or better prepare to train incoming employees, especially as they confront an aging workforce[312]. It can help municipalities with regulatory compliance, such as in the case of Newark Water and Sewer in New Jersey, where adoption of an AI-powered more centralized management system enhanced operation and data collection for reporting that made complying with state regulations easier[313]. These digital technologies also enable better tracking of GHG emissions from facilities (especially relevant for high energy-using wastewater treatment) and can reduce cybersecurity risks, thus weakening two negative connections in our CLD.

303) Hung et al. (2014)
304) San Francisco Public Utilities Commission (n.d)
305) Hung et al. (2014)
306) International Water Association (2016)
307) MIT Technology Review (2024)
308) WaterWorld (2016) WaterWorld (2016)
309) Edinger (2021)
310) ASCE (2021)
311) Schneider Electric (2023)
312) Hatler (2023)
313) Edinger (2021)

Digital solutions for the water space are already gaining market traction – in fact, economic benefits appear to be the main driver behind their spread, followed by regulation and climate change[314]. Estimates for return on investments for digital solutions vary considerably at the moment, because methods to measure the cost reduction and increased efficiency of the new technologies can differ a lot between utilities. A conservative estimate is about 14%[315], suggesting that water automation can drive substantial returns. Experts have estimated that investments in digital solutions within the water space globally will double between 2021 to 2030, from $25.9 billion to $55.2 billion[316]. Furthermore, according to Schneider Electric's own experience and estimates, digital solutions in water and wastewater treatment have the potential to optimize energy consumption by up to 30%, increase operational efficiency by up to 25%, and reduce the total cost of ownership by up to 20%[317]. So far, large municipalities have seen the biggest adoption. While a more nascent market, technologies tailored for industry-specific requirements and for smaller water utilities — increasing affordability, ease of use, and compatibility — show a lot of promise too.

Digital infrastructure can also amplify positive impacts of the earlier mentioned solutions like NBS. The city of Philadelphia, for example, implemented its Clean Waters program using NBS like permeable pavements, green roofs, and rain gardens in combination with smart water technologies to monitor leaks and improve efficiency in their water distribution networks[318]. Consequently, the city has been able to exceed their 10-year pollution reduction goal and has prevented three billion gallons of wastewater from entering their local waterways[319]. Their plan has not only generated important environmental benefits like improving water quality, air quality, and supporting wildlife, but also has reportedly created local jobs, promoted tourism and recreation, and increased property values. Moreover, it has allowed for extensive community collaboration, and has encouraged the development of healthier communities. This showcases how synergistic solutions such as presented in this paper can have benefits across many environmental, social, and financial factors, enhancing resilience against disturbances not only in water systems but the overall societal system.

Exhibit 37. Key statistics on digital solutions for water.



Technological revolution

Digital solutions fall under the broader societal trend of digitalization. Digital innovations like AI, blockchain, the internet of things, Augmented Reality, LiDAR, among others, have been transforming every aspect of our lives, including business, transportation, health, finance, buildings, education, and communication. In fact, this trend is so ubiquitous that it needs no further explanation here.

Innovative funding instruments

The crucial importance of funding for water infrastructure has been discussed, as well as the traditional sources of the public budget and water rates. Because these have not always been sufficient by themselves, it's worth looking at a few innovations in this space. It's important to note that given the interconnectedness of sustainability issues, of which water is one, raising of additional funds should happen in alignment with overall sustainability principles. Mechanisms that promote investment in water infrastructure and incentivize sustainable practices include green and blue bonds or loans, and payment for ecosystem services (PES).

Green and blue bonds, and green loans

Green bonds and blue bonds facilitate collaboration between the private and public sectors to fund water infrastructure improvements. Green loans are similar to green bonds in their purpose and construction, but the funding comes from a bank rather than the investor market[320].

Green and blue bonds concern large amounts raised by institutional or multinational players which are used to finance large projects that have positive effects on the environment. Green bonds concern the broader environment, including but not limited to water, and blue bonds concern specifically the water space. Green bonds are most common practice; in 2023, the World Bank made commitments totaling $2.2 billion and disbursed $955 million to green bond eligible projects[321]. Most of these were climate-related, but results for that year also include 17 million m3 of water savings, 12 million m3 of wastewater treated, reused, or avoided, and 12,440 tons of raw/untreated sewage sludge treated and disposed of. The United Kingdom company Anglian Water, for example, which provides water and wastewater treatment for the Anglian Water Authority, issued a £250 million green bond with a

314) Daniel et al. (2023)
315) Grundfos (2020)
316) Bluefield Research (2022)
317) Schneider Electric (2018)
318) Brears (2018)
319) Philadelphia Water Department (n.d.)
320) Chase (2021)
321) The World Bank (2024)

1.652% interest rate and maturity of 2025 to fund projects in water abstraction, drought and flood resilience, water recycling, and water resource management projects[322]. Its Chalton Water Recycling Center has now become one of the largest sand and water filtration centers in all of Europe. Anglian Water also used the funding for projects in broader ecosystem restoration, by constructing a wetland environment along another water recycling facility in Ingoldishorpe, Norfolk, to improve the health of the neighboring River Ingol[323]. Although more popular in Europe at the moment, green bonds have been used in the US too. Asheville, North Carolina, for example, used a green bond in 2007 when it experienced leakage and pressure stress in the city's water network to fund infrastructure repairs, including water tanks optimization and the replacement of failing water lines and old valves[324]. Their project was so successful that in 2020, they decided to issue a second green bond aimed at improving the health of their North Fork Dam, a $40 million bond with a 2.1% rate of return.

Blue bonds have been part of funding for European water projects such as the $20 billion Nordic-Baltic Blue Bond that has been used in water and wastewater treatment, pollution minimization, and enhancing water-related climate-change resilience[325]. Blue bonds have not yet been used in the US, but it's possible the practice might spread from Europe in the future.

European water projects have also been funded using green loans, such as in the Antwerp inter-municipal water company called Water-link, which €46 million loan was provided by BNP Paribas Fortis[326]. The green loan enabled them to implement 200,000 digital meters to improve water volume calculations, reduce leakage, and develop an intelligent control center. There have been many green loans in the US, but those seem to have focused on energy and climate related projects so far. This could of course change. There are no blue loans yet, perhaps that's another financial innovation that could arise in the upcoming years.

Payment for ecosystem services

Payment for ecosystem services (PES) is another funding instrument that, although it has been in use for decades, continues to innovate and spread in application[327]. Ecosystems provide humans with a range of essential benefits known as ecosystem services, which are categorized into four types: supporting, regulating, provisioning, and cultural[328]. Aquatic ecosystems are of course part of this, with services that, among other things, include water purification, water provisioning, and carbon sequestration (oceans are the largest carbon sink in the world[329]). PES are an attempt to value these services more accurately in order to conserve them, by offering ongoing compensation to a country, community or individual for preserving an ecosystem and thus its services.

There are three primary types of PES markets: public payment programs for private stakeholders, structured markets with open trading, and private, self-organized agreements[330]. Especially when it concerns public payment programs, it can be beneficial to assess the probability of success of a PES by surveying the concerned population that would be paying with their taxes with a "willingness to pay" for such services. Aligning the payments accordingly, if possible, creates stakeholder buy-in[331]. PES can in certain cases also reduce large income and wealth disparities between buyers and providers of ecosystem services, adding social benefits to the scheme on top of the environmental ones[332].

Coral on Belize's coastal ocean, which enjoys enhanced protection now though a PES and blue bond structure.

322) Brears (2018)
323) Brears (2018)
324) NC Resilience Exchange (2024)
325) Brears (2019a)
326) Brears (2019b)
327) UN Environmental Program (2008)
328) E.g., Herrington (2023a)
329) United Nations (2023)
330) James & Sills (2019)
331) Wang et al (2017)
332) Wang et al (2017)

Public payment programs often involve government-led initiatives, where funds are provided directly from a government agency to an institution or private landowners. One major example was the so called "debt-for-nature swap" with Belize in 2021, with the involvement of US-based nonprofit The Nature Conservancy. In exchange for a $553 million debt reduction towards the US, the Belizean government agreed to increase its Biodiversity Protection Zones of its marine ecosystem from 15.9% to 30%[333] (30% conservation of wildlife water and land is the minimum for biodiversity protection and restoration, according to experts[334]). This transaction, which was also structured as a blue bond, allowed Belize to rid itself of about a quarter of the country's total debt, freeing up $189 million over the next 20 years to go towards its conservation commitment.

Structured markets operate within either regulated frameworks, such as with a price cap or floor, or within voluntary market systems. Companies buying carbon credits from landowners who plant trees to offset their GHG emissions are an example of this. Lastly, self-organized private agreements occur when a user of an ecosystem service directly contracts with the service provider. An example is a group of local businesses in a watershed area voluntarily paying a nearby landowner to maintain a forest on their property to ensure clean water supply for their operations, with the payment amount based on the quality of water delivered, thus creating a direct economic incentive for the landowner to protect the ecosystem[335].

Another example of a PES was mentioned briefly already in the nature-based solutions section: The NYC Catskills watershed management plan to improve the quality and safety of the city's drinking water[336]. NYC used PES schemes to incentivize the preservation of the ecosystem services, including purification, provided by the Catskill watershed further upstate, where the water was coming from. As mentioned, this approach avoided the need for additional water treatment plants, which would have cost an estimated $6 billion plus $200-$300 million annually for maintenance, making the PES highly cost-effective.

Today, PES for watershed services are widespread, partly due to the additional benefits of watershed conservation, such as flood protection, which have become widely recognized. More than $36 billion is estimated to be exchanged annually for activities that support and conserve ecosystem services[337] . Certain conditions, however, are essential for the long-term success of PES in achieving desired social and ecological goals[338]. First, baseline data and clear metrics on the ecosystem service in question is critical to structure and inform management plans that ensure sustainability. Case studies also highlight the importance of monitoring — something which digital solutions could support, as also discussed in general in an earlier SRI paper on green digital solutions for biodiversity action[339]. Additionally, PES and management plans must be adaptive, considering the dynamic nature of ecosystems and adjusting conservation strategies accordingly.

Sustainable finance

Green and blue bonds, PES, and green loans fall under the general trend of "sustainable finance", a growing market that also includes instruments like climate bonds, social bonds, and sustainability loans. The total sustainable finance market amounted to $6.61 trillion in 2024 and is expected to continue growing in the upcoming decade and beyond[340]. These large projects require robust yet agile management, including local community and stakeholder engagement, a well-designed framework for accountability, and well-defined incentives that provide benefits for both providers and buyers. In short, an indispensable element of sustainable finance projects is cooperation. This necessity extends beyond sustainable finance to successful Regeneration models in general, which brings us to the next and last solution.

View of the Catskills mountains with Ashokan reservoir in the foreground in the Hudson valley, New York.

333) The Nature Conservancy (n.d.)
334) E.g., Herrington (2023a)
335) Braybrook & Barrera (2016)
336) Isakson, R.S. (2002)
337) Salzman, et al (2018)
338) Herrington (2023b)
339) Börner, et al. (2017)
340) Presedence research (2024)

Cooperation

The solutions mentioned in this section so far require increased communication, coordination, and collaboration between government entities, governments and businesses, as well as with and between citizens[341]. Tiered water rates necessitate extensive dialogue with all different kind of water users to establish truly needs-based tier thresholds. Although nature-based solutions don't usually impose additional financing demands, they do require redistribution and redirection of existing funds, which can prove challenging in an environment of competing and sometimes even opposing priorities at various government levels and organizations. Nature-based solutions can also face implementation barriers such as unfavorable legacy regulation historically developed around grey infrastructure approaches[342]. Digital solutions often face the same barrier of unconducive regulation, and other barriers too, such as a lack of technical expertise, and the need for education programs which ideally are well-publicized to the public and coordinated between government and water distributors[343]. Digital infrastructure also requires high up-front financial investments, which can be provided with innovative funding, but these instruments too require collaboration between large organizations, governments, and / or communities being paid for ecosystem maintenance in the case of PES. All of these challenges and more — such as the need for a more diversified water sources and sinks in order to achieve water neutrality in general — can be overcome through better alignment between water systems, agencies, and other parties. According to experts, this requires better coordinated and executed planning, design, and operation, increased monitoring and enforcement, and addressing equity and justice as a standard practice[344]. Such cross- and inter-sectoral collaboration can sometimes prove difficult in a space like water infrastructure, with its many stakeholders and de-centralized management. While an in-depth discussion of best practices in stakeholder dialogues, cross-company and public-private partnerships, legislative change-making, and streamlining processes falls outside of this document's scope, it's important this section is not interpreted as a list of stand-alone-sufficient technical fixes. This echoes the last paragraph of the previous section with the CLD analysis, stating that the kind of Regeneration nexus identified there will only come about through a conscious decision and deliberate efforts on the part of water system actors.

Most of the literature is focused on the need for improved cooperation between major players like the large Community Water Systems (CWSs), which is understandable given they provide water to the large majority of the US population. But on the other end of the scale, there is a notable organizational form of cooperation in the water space as a private entity: the cooperative. This is an interesting example to highlight under this solution because cooperatives are comprised of locals, thus representing a concrete way that citizens can exert their influence in the water system through direct action.

Cooperatives

Cooperatives are growing in numbers and, as mentioned, these generally provide services against lower rates and of higher quality. There are 3,300 water cooperatives, or coops, in the US, typically serving communities of 500 to 3,000 people[345]. Water cooperatives date back to the Industrial Revolution when they arose as an alternative solution to Public Water Suppliers (PWS), historically focusing on rural areas which often lacked accessibility to water services. The structure of water cooperatives hinges on seven pillars which include inclusive and voluntary membership, democratic governance, proportional financial responsibilities and benefits, autonomy and independence, a commitment to continuous education and training, cross-cooperative collaboration, and an emphasis on community wellbeing[346]. Anyone can join a cooperative on a voluntary basis, after which the member is expected to contribute equally to the capital needed by their cooperative and will receive equal compensation in the form of benefits (in this case water provisions). Amongst members of cooperatives, decisions are made in a democratic fashion, meaning that members who actively participate have equal voting rights in the decision-making process of the organization[347]. There are various types of cooperatives, ranging from producer-owned, consumer-owned, and worker-owned[348]. In the US, consumer-owned cooperatives, or those cooperatives who are owned and managed by consumers themselves, are more common[349].

Water cooperatives face similar challenges as other water systems when it comes to cooperation, and the general challenges as laid out in this document, including rising water scarcity and quality challenges. Sometimes these challenges differ in detail due to the cooperative organization form. Coops too face a risk

Cooperation is key for a more sustainable water system.

341) Crosson et al. (2024)
342) UNESCO World Water Assessment Programme (2018)
343) Hatler (2023)
344) Crosson et al. (2024)
345) University of Wisconsin Center for Cooperatives (n.d.)
346) Young (2022)
347) Ruiz-Mier & van Ginneken (2006)
348) Ruiz-Mier & van Ginneken (2006)
349) University of Wisconsin Center for Cooperatives (n.d.)

of a shortage of skilled workers, for example, but in this case the challenge is to educate and upskill the cooperative members instead of attracting outside water workers. Despite more democratic decision-making processes, inequality challenges persist with coops too, in this context around achieving equitable management of member responsibilities and integration of the various perspectives of salaried versus volunteer representatives[(350)]. Some challenges are lighter for coops compared to other water systems, such as monitoring and enforcement because of aligned incentives between providers and users (people typically try to avoid polluting their own drinking water sources). On the other hand, there are challenges specific to coops, such as the free rider problem: people who do not contribute to the coop but still enjoy the service because they reside in the community. In certain situations, this makes government-owned water supply a more effective way to deliver water to residents. For example, paying taxes is non-optional, so (leaving the topic of tax evasion aside) the free-loading problem does not exist for water municipalities. Additionally, publicly owned water systems are more effective over larger areas because they can integrate needs in the overall government infrastructure planning.

Nevertheless, cooperatives can be an advantageous organizational form for providing affordable, safe, and stable water provisions for smaller areas with sometimes specific needs[(351)]. The private organization form might work better for these low population areas, who might otherwise have difficulty representing their interests in overall government functioning. And because of cooperatives' not-for-profit nature, they can focus on other factors outside profitability, which can sometimes enable better long-term resource allocation, increased affordability for the water users, and greater community engagement. Less pressure to deliver growing profits every quarter or year allows for long-term investments in efficiency and quality, for example, or to charge lower prices when liquidity allows. Additionally, unlike some investors in for-profit water systems – who in some cases might withdraw investments quickly if other opportunities promise more profit – cooperative members have a stronger incentive to reinvest their profits back into the cooperative given they derive value directly from the use of the water service it provides[(352)]. The greater community engagement is also partially derived from increased transparency. Given the equitable decision-making process and overall aligned incentives, there is typically no incentive for any asymmetric information; in fact, there is an incentive to reduce it for ease of communication.

Perhaps these member incentives and broader community benefits and engagement explain why coops have a significantly lower failure rate than for-profit companies in general: 10% versus at least 60%[(353)]. These figures are for cooperatives in general, not just in water, which shows how water coops are embedded in an overall trend in the US of cooperatives being the fastest growing sector in the country[(554)]. This also illustrates how coops can be thriving and successful businesses, not to be confused with charities. The Illinois-based EJ Water Cooperative is a good example. Serving twelve distinct counties and a total of 77,833 people, this not-for-profit cooperative was founded in 1988 on the promise to deliver safe and affordable water to its community members[(355)]. Members of EJ Water have representation in decision-making, including through online tools. In 2019, the EJ Water Cooperative won the Best Tasting Water Award, and additionally, that same year were also the recipient of the Effingham Chamber's Business in Excellence Award[(356)].

Prairie Creek Falls, Illinois.

350) Young (2022)
351) Young (2022)
352) Ruiz-Mier & van Ginneken (2006)
353) Nembhard (2014)
354) Rausch (2024)
355) Environmental Policy Innovation Center (n.d.)
356) EJ Water Cooperative Inc. (n.d)

Chapter 4. Conclusion

This report started with a brief mention of the global water crisis in Chapter 1, before zooming in on the water crisis that the US currently faces: an infrastructure so far past its prime that its state negatively impacts both the quality and availability of the water that it distributes. This is not America's first water crisis, and there are ways to overcome this one too.

To identify them, Chapter 2 explored the relevant environmental, technical, and social factors in the US water system, and the interactions between them. The water cycle was covered, and how the health of aquatic ecosystems supports human health and activity, from industrial to recreational. We discussed how society's water use is not sustainable, neither in terms of the quantities used nor how much we pollute it, and how climate change and broader ecological damage are further acerbating pressures on both these aspects.

We then turned to the technical aspects, starting with a description of the physical water infrastructure: the water suppliers and distributors (water systems), pipes, dams, and water and wastewater treatment facilities. Water systems can be private or public, and vary significantly in size. Large municipalities supply by far the biggest share of the population, but private water systems play an important complementary role, by supplying certain rural areas or private facilities. Industrial use also can be significantly different from domestic water use, which is why after the general description of the water landscape and how water is circulated through society from sourcing, distribution, and treatment, municipal and industrial water infrastructures were discussed in more detail in separate sections. The last section covered the major challenges for the water infrastructure: outdatedness, first and foremost, but also insufficient investment capital, poor water quality, rising water scarcity, and cybersecurity risks. All of these challenges are of course interrelated, and further interact with even bigger systems like the overall US infrastructure and the US energy system.

Social factors encompass regulation, and various other government policies which influence the economic and social incentives of citizens. Regulation on water quality is federal, while quantity in terms of allocation is typically at the state and more local levels. Quantity in terms of water efficiency is incentivized at the federal level through certification and related incentives. Funding and politics are related, as most of the investment capital for maintenance and upgrades comes from the public budget. The Bipartisan Infrastructure Law has made significantly more funds available for upgrades. The government also influences water rates to some extent, which are another source of funding for water systems. These directly influence water affordability, i.e., the ability for low-income households to pay for their basic water needs. Several pricing structures were discussed: fixed, uniform, and tiered rates. Other government initiatives around the economic aspects of water include setting up water markets and compensating low-income households directly for water costs. There are also government initiatives on non-economic social aspects, including awareness campaigns to educate the public on water issues, relevant water policy changes, and water efficiency standards, among other things. There are many feedback loops between these various aspects, as citizen concern or confidence around drinking water and trust in government influence elections and general attitudes towards water conservation. The chapter ended with another zoom-out to the bigger systems, which in this case included the overall government budget and broader economy.

When all these interactions were combined into one large causal loop diagram at the start of Chapter 3, analysis revealed three broad areas with potential leverage in the water system: government's central influence, citizen's underused influence, and working for nature. While the role of government is crucial for well-functioning water systems in the US, the analysis in this document indicates that more can be achieved by activating the underused power of citizens and transforming businesses towards regenerative business models, in order to reduce some of the pressures on government, including for funding. To makes things a bit more concrete, real-life examples of emerging solutions covering at least one of those areas, and often more than one, were discussed in the Solutions part that rounded out the chapter.

Sign on the sidewalk in key West, Florida.

One such solution could come in the form of an expanded use of well-designed tiered water rates, which can strike an effective balance between protecting affordability by virtue of low pricing for basic water use, and incentivizing water conservation through disproportionally higher water prices above such needs-based amounts. While government funding of water infrastructure has been and will continue to be imperative, tiered water rates could alleviate some funding pressures in a way that appeals to a sense of fairness from the public, as a disproportionate share of this financial capital would be collected from "water wasters". Nature-based solutions such as green roofs, various permeable walkways, waterfront parks, and wetland restoration, are another category of solutions. They offer funding relief as they are typically no more expensive to construct compared to "grey infrastructure" alternatives, yet tend to offer better value for money in the long run when factoring in avoided costs. Despite this, legislation around their funding and construction is not always conducive yet, and should be improved. The same point around necessary legislative changes is true for digital solutions like real-time monitoring of water quality and quantity, automated processing, and AI-enabled predictive maintenance. Digital infrastructure does require up-front investments; however, it also offers significant water, energy, and cost savings over time which are relatively easy to measure. Other, more innovative, ways to fund water infrastructure upgrades than taxes and water rates were also briefly discussed: green bonds, blue bonds, green loans, and payment for ecosystem services (PES). Green bonds, blue bonds, green loans, come from large multilateral and multinational institutions, while PES can also be paid to small communities or even single individuals. The common thread weaving these solutions together is the final "solution" of increased cooperation within and between water systems, as well as general government, business sectors, and citizens in general, in the form of increased monitoring and enforcement, addressing equity and justice as a standard practice, and better coordinated planning, design, and operation.

Further research is necessary for all the above-mentioned policies and solutions. The optimal design of water rates is crucial, as well as greatly dependent on the kind of user, which begs questions on what design and stakeholder consultation guidelines exist and could be proposed. Design and implementation details of digital solutions and nature-based solutions, including their combinations, differ greatly too depending on geographical location and whether industrial or residential users are concerned, prompting the needs for more detailed studies on these. Similarly, the corporate sector requires its own more detailed study on regenerative practices, models, products, services, and ultimately, pathways towards becoming a water-positive business. Do any of the innovative funding instruments provide relevant lessons for making these water-positive business models profitable? And if cooperation is crucial, what organizational models in government, business, and between citizens can improve cooperation between and within these players? What concrete and feasible policies shape the optimal conditions for business and citizens to take meaningful action towards regeneration?

If those are more questions than the reader had at the start of this document, then we humbly suggest it has achieved its goal: giving an overview of all the relevant aspects around US water infrastructure and illuminating necessary and feasible ways forward, still to be carved out.

Grand Canyon, Arizona, which has been carved out by water over millennia

Appendices

Tree in Lake Cabo, Texas.

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