EXTREME DECENTRALIZED WATER TREATMENT: Exploring the Future of Premise-Scale Water Treatment and Reuse

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Disclaimer

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INTRODUCTION

Access to an adequate quantity of piped water and management of wastewater produced in homes and businesses is an expectation of city dwellers in wealthy countries, and an aspiration for many people living in rapidly developing cities in low- and middle-income countries. It is also crucial to public health and protection of the environment. For well over a century, municipal drinking water provision and wastewater management have been made possible by large investments in centralized systems in which fresh water passes through a small number of drinking water treatment plants before being distributed through a vast underground pipe network to buildings throughout the city (Sedlak 2014). After it is used, wastewater is collected in underground sewers that route it to treatment plants prior to its discharge to the environment. In some water-stressed cities, a fraction of the treated wastewater undergoes additional treatment prior to reuse. This recycled water often is returned to users through another dedicated water distribution system, which is designated in many places with purple pipes (*non-potable water reuse*). Alternatively, treated wastewater may be subjected to advanced treatment (e.g., reverse osmosis followed by advanced oxidation) prior to being returned to the drinking water supply (*potable water reuse*).

Due to the logistical challenges of moving large quantities of recycled water from centralized wastewater treatment plants, which are often located on the edges of cities, to potential users within the city, some small-scale water recycling facilities have been built closer to where the recycled water is reused. Such operations, which are sometimes referred to as *distributed water recycling systems*, are often easier to build and operate than centralized water recycling systems, because they require a less extensive water distribution infrastructure and can be situated closer to users of recycled water (e.g., high-density housing developments, industrial water users, golf courses).

Although distributed water reuse solves some of the problems associated with the construction of a dedicated water distribution system for non-potable water throughout an entire city, the high relative costs, regulatory complexities, and risks of unintentional cross-connections between recycled water and potable water pipes have limited the spread of such systems. As an alternative, a new approach to water recycling referred to as decentralized water reuse may have promising advantages for utilities, developers and entrepreneurs. This approach usually involves the recycling and reuse of water within a building or single-family home, at individual premise-scale. Decentralized water reuse systems often include connections to potable water from a municipal water system providing a small fraction of the water used in the building, and a centralized sewer system serving as a means of disposing of salt and organic matter produced by the recycling system.

Distributed water recycling systems have made considerable progress in cities where there is a recognition of the need to address water scarcity and where partnerships have been built between utilities, building operators and regulatory authorities. Projects located in Tokyo, Bangalore and San Francisco (see text boxes) exemplify the drivers for adoption of distributed water recycling systems, as well as the institutional and technological approaches employed to enable successful projects. In North America, there is growing interest and enthusiasm for the practice of distributed water reuse, as evidenced by the activities of the National Blue Ribbon Commission for Onsite Non-Potable Water Systems[1], the US EPA thorough its Water Reuse Action Plan[2], and the growing number of events dedicated to the topic by stakeholder groups such as the Water Environment Federation[3], the WateReuse Association[4] and the Water Research Foundation[5].

1 *https://watereuse.org/educate/national-blue-ribbon-commission-for-onsite-non-potable-water-systems/*

2 *https://www.epa.gov/waterreuse/water-reuse-action-plan*

3 *https://www.wef.org/*

4 *https://watereuse.org/wp-content/uploads/2021/08/Onsite-Committee-Fact-Sheet_2021.pdf*

5 *https://www.waterrf.org/search?topic=Decentralized%20Systems*

Some of the earliest projects, which required subsidies or government grants, were driven by the desire of water professionals to demonstrate the possibility of recycling water at the building or district scale. These projects attracted considerable attention but were not followed up by the construction of many additional projects. More recently, citywide ordinances requiring the installation of water recycling systems in new buildings above a certain size have driven construction activities in several cities. Such ordinances provide a means of shifting some of the cost of expanding water services to developers and new building occupants, and are leading to a gradual increase in the deployment of this approach when the added costs are not an impediment to project development. Ultimately, the greatest promise for distributed water recycling systems is that costs will drop to a point at which their installation will offer an incentive for their use in new construction. For example, in parts of North America and Western Europe, installation of water recycling systems in multi-family dwellings can already be justified by savings on water tariffs (Garrido-Baserba et al. 2022), with return on investment in less than ten years, provided that the utility does not charge the building occupants high fees for access to the water distribution and wastewater collection system. Beyond the advantages to building owners and occupants, adoption of distributed water recycling systems offers the possibility of creating greater resiliency by reducing per capita water demand and providing a means of providing water during times of shortage or service interruptions. They also offer opportunities to capture waste heat, recover resources from wastewater, and reduce the mass of nutrients and organic contaminants discharged to surface waters.

The current generation of treatment technologies typically recycle less than half of the wastewater produced within the building. In part, this is due to concerns about costs, but it is also determined by constraints put upon uses of recycled water in buildings. Although it is technically feasible to treat wastewater to a point at which it can be used for drinking, cooking and bathing, or to employ rooftop rainwater collection for potable purposes, such projects have rarely been built due to concerns about safety. Single-family homes, multi-family buildings or commercial buildings that operate without connections to piped water or sewers are sometimes referred to as *extreme decentralization*. Although it is difficult to make a case for such systems within cities, where piped water and sewer systems are readily available, such systems have the potential to help address water scarcity and contamination in rural settings. They also have potential for application on the edges of cities, where low population densities and the ability of existing water and sewer systems to handle additional connections is limited. In one example, the City of San Francisco has piloted "PureWaterSF." This research-scale system purifies water that meets drinking standards from wastewater generated onsite at the headquarters of the San Francisco Public Utilities Commission (SFPUC)[6].

Although existing technologies have proven to be adequate for the current generation of distributed water recycling systems, there is considerable room for improvement. The National Alliance for Water Innovation (NAWI) was founded with a mission of conducting research to lower costs and improve the feasibility of advanced technologies that could help make non-traditional water sources a larger part of the nation's water portfolio. As part of NAWI's efforts to identify problems where research and development could enable non-traditional water sources to meet pressing national needs, the topic of water reuse was identified as a high priority due to the widespread use of technologies that were recently commercialized in existing systems and the relatively large number of factors that increased the cost of treatment (e.g., uncertainties about health risks that drove engineers to employ treatment trains with large margins of safety) as well as factors that limited the locations where facilities could be built (e.g., challenges associated with brine concentrate disposal). Based on NAWI's survey of recent advances in the water sector [7], it is reasonable to expect that advancements in sensing, computing, materials science and biotechnology will decrease the costs and increase the reliability of the components used in both distributed and decentralized water recycling systems.

6 See: *https://sfpuc.org/programs/future-water-supply-planning/innovations/purewatersf*

7 NAWI's recent publications: *https://www.nawihub.org/knowledge/roadmap-publication-series/*

To gain insight into the potential for advances in water treatment technology to lower costs and facilitate the spread of distributed water treatment systems, NAWI and Stanford's Water in the West convened a meeting of experts on February 9, 2023, at Stanford University. This report shares the findings of a workshop that brought together researchers, industry experts, practitioners, policymakers and other stakeholders to discuss the current state of knowledge in extreme decentralized water treatment systems, and to identify the areas where further research and development are needed. Unlike centralized water recycling systems, the current generation of distributed water recycling systems are still in an early phase of development with fewer than about 4000 systems installed worldwide. Furthermore, most utilities, building designers, regulatory agencies and equipment companies have limited experience with these systems. To provide insight into future research and development needs, as well as issues requiring further clarification, the workshop focused on several key themes, including technology advancements, public health risks of system deployment, economic considerations and regulatory frameworks. The objective of this report is to provide a comprehensive overview of the discussions and insights gained during the workshop.

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Tokyo's Pioneering Journey into Building-Scale Water Infrastructure

Japan presents an innovative model for sustainable urban development in the realm of water management. More than 2,500 individual buildings in the country utilize in-building wastewater reclamation and rainwater harvesting systems, an alternative approach to centralized treatment that creates sustainable, resilient structures (Kimura et al. 2013).

These systems treat different types of wastewaters within each building, including domestic sewage and graywater. The treated water is then used for various purposes like toilet flushing, cooling, garden watering, car cleaning and even fire protection. The emphasis is on reusing water within the building where it was generated, dramatically reducing the strain on centralized sewage systems and providing a resilient solution to water management.

Membrane bioreactor (MBR) technology, owing to its suitability for on-site wastewater reclamation, has been widely adopted in these systems. The main advantage of MBR is its compact design, high water treatment efficiency and adaptability to changes in inflow, making it highly effective for on-site wastewater treatment in diverse buildings ranging from offices and schools to hospitals and factories.

This shift towards building-scale water management has been facilitated by various factors, such as supportive local regulations, favorable tax policies, and technological expertise in designing and operating these systems. Further, the availability of a design manual and clearly defined water quality requirements for reclaimed water have further bolstered the adoption of on-site wastewater reclamation.

The largest proportion of these systems are in public office buildings, although businesses, schools, hospitals, public parks and factories also account for significant portions of these implementations. The adoption of on-site water reclamation systems is increasingly viewed as an emblem of environmental responsibility and resilience, particularly in a disaster-prone country like Japan. This not only reduces the demand on public water supplies but also allows these buildings to maintain operational continuity in the face of disasters, acting as potential rescue centers.

These building-level water reclamation systems in Japan serve as a viable model for other countries seeking to promote sustainable water use, resilience in the face of climatic shocks and environmental responsibility. They offer an example of how technological innovation and supportive policy frameworks can drive sustainable urban development and resource conservation.

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Implementation of Onsite Non-Potable Water Systems (ONWS) in San Francisco

The success story of San Francisco's Onsite Non-Potable Water Systems (ONWS) over the last decade is a testament to strategic collaboration among public utilities, academia, NGOs and other stakeholders, driven by several vital components that fostered a thriving ecosystem of water reuse technologies (Afghani et al. 2023).

Policy changes and financial incentives played a pivotal role in kickstarting the local market. The SFPUC revamped regulations and introduced financial incentives, sparking economic viability for ONWS and igniting a surge of innovation, thus creating a conducive environment for local start-ups offering cutting-edge water systems.

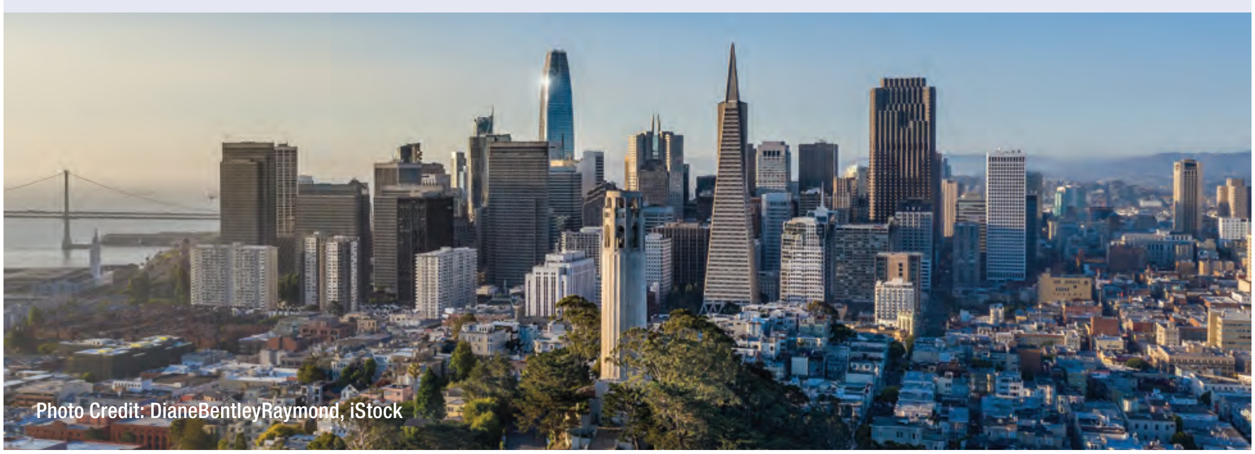
The launch of the design-build-operate (DBO) model was another major breakthrough. By simplifying the process of ONWS implementation, this model facilitated permitting, enhanced operational quality and guaranteed long-term revenue for companies. The success of the DBO model hinged on the flexibility of the market and its adaptability to evolving circumstances.

Stakeholder engagement has been another key component of the success story. The SFPUC undertook extensive outreach programs, workshops and conferences, sharing necessary knowledge and cultivating a sense of community around the cause. This communal approach helped in overcoming hurdles, identifying research needs and garnering widespread support for the initiative.

The introduction of a Risk-Based Framework, developed in collaboration with utility and public health professionals through the Blue-Ribbon Commission for Onsite Non-Potable Reuse, was instrumental for San Francisco and contributing agencies around the country. It provided clear guidelines on the equipment, design, construction, operation and maintenance of ONWS. Its application was not just confined to San Francisco but extended to other US jurisdictions, demonstrating its effectiveness and scalability.

Credibility-building activities also played a crucial role in the program's success. The installation of a highly visible non-potable water recycling project project at the SFPUC headquarters, along with other landmark buildings, like 181 Fremont and the Salesforce Tower, heightened the program's legitimacy. The voluntary adoption of ONWS by Silicon Valley's tech giants further fortified its reputation.

Nevertheless, despite the notable triumphs, the road ahead has its share of challenges. High capital and operational expenses, a dearth of technical expertise among operators and the requirement for economies of scale underline the complexity of transforming ONWS into a globally viable solution to urban water issues. However, with an accredited training program for ONWS operators on the horizon and continued exploration of innovative business models, the prospects of ONWS look bright.



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Adoption and Adaptation of Onsite Non-Potable Water Systems (ONWS) in Bengaluru

In Bengalaru, India, the adoption of building-scale water treatment presents a fascinating landscape, echoing a distinct narrative of city planning and entrepreneurial dynamism. The city's journey features a unique blend of policy directives, innovative industry response and consumer-centric approaches (Miörner et al. 2023). This shift is seen in the form of small-scale sewage treatment plants (SSTPs) that are mandated to be included in all new construction and certain existing buildings. These systems are often contained within the building complex, treating wastewater for reuse in non-potable applications, like gardening and toilet flushing, contributing to a circular water economy at the community level.

First, a "top-down," policy-induced, technology-agnostic approach by local and regional regulators set the stage for a burgeoning ONWS industry. The resultant entrepreneurial ecosystem brought together a variety of firms, each with its unique focus on design, construction, operation or maintenance of SSTPs, imbuing the field with an entrepreneurial spirit akin to that seen in California's renewable energy sector.

Next, a clear pivot toward market-driven implementation precipitated a demand-side dynamic. Lead users, such as resident welfare associations (RWAs), spearheaded the push for better technologies, affordable operational solutions, and economically viable business models. This market pressure ushered in an era of innovation.

Bengaluru has seen a gradual increase in the legitimacy of ONWS. Even in the face of resistance, RWAs and the general public increasingly acknowledged the systems' potential, treating them as a normal feature of urban life.

Despite the parallels with other global implementations of building-scale treatment and reuse, Bengaluru's journey has included unique challenges. The need for complementary governance structures and regulatory standards is acutely felt as the city grapples with ensuring accountability and quality in the rapidly growing ONWS market. Furthermore, concerns surrounding the health and safety of workers interacting with these systems underline the urgency for comprehensive regulation.

Bengaluru's story is one of policy-induced innovation and adaptation in the face of necessity. It mirrors San Francisco in its embrace of forward-thinking solutions but is distinguished by its distinct cultural and regulatory landscape. It serves as a reminder that while solutions can be replicated, context matters, and adaptation remains key in any sustainability transition.


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RESEARCH MOTIVATION

The motivation for the workshop organizers, including participants of Stanford University, UC Berkeley, the National Alliance for Water Innovation and the SFPUC, was to explore the potential of extreme decentralized water treatment systems as a viable alternative to centralized water treatment. An emerging body of research, including publications such as “The Third Route: A techno-economic evaluation of extreme water and wastewater decentralization (Garrido-Baserba et al. 2022),” suggests that premise-scale systems may already be economically attractive to building owners. By lowering their costs, improving their performance and resolving institutional issues that often make it difficult to obtain permits for such systems, this approach might become an effective way for water managers to respond to water scarcity and to improve the resiliency of water systems.

METHODS

The workshop was organized into four sessions focused on different aspects of building-scale water recycling. Participants worked together to identify key drivers for change, barriers in the current approach to water system operation that have the potential to slow technology adoption and research needed to advance the practice. Presentations, demonstrations, panel discussions and breakout sessions were used to gain insights, share experiences and engage with professionals from different aspects of the innovation ecosystem. The workshop also included a review of existing technologies and case studies, a creative visioning exercise, as well as facilitated discussions on potential future developments.

To facilitate a comprehensive and in-depth exploration of both the established approaches to building-scale water recycling, as well as emerging approaches for creating buildings that could operate without connections to municipal water and sewer systems, the workshop employed a multi-faceted approach with discussions of immediate needs and longer-term developments. The event brought together a diverse group of participants, including researchers, industry experts, policymakers, utility operators and other stakeholders to foster a collaborative and interdisciplinary discussion.

RESULTS AND DISCUSSION

The Importance of Definitions

Premise-scale water recycling encompasses a broad range of systems and approaches, which can lead to varying interpretations and conflicting uses of key terms. Workshop attendees discussed the need for clear definitions of centralized, decentralized and distributed systems, as well as related terms, such as extreme decentralized, onsite and hybrid systems. The National Blue Ribbon Commission for Onsite Non-potable Water Systems, the Water Environment Federation (WEF) and other organizations are working on the development of terminology that is accepted within the professional community. Nevertheless, it is important to define terms when they are introduced to ensure a common understanding.

Water reuse often involves separation of wastewater sources, as well as the production of recycled water of different qualities (i.e., fit-for-purpose water). Terms like black water (for combined urine and feces), brown water (feces only) and yellow water (urine) are generally accepted within the professional community. Graywater usually refers to the waste that is not normally sent down the toilet. The use of colors to define wastewater sources sometimes causes challenges in discussing fit-for-purpose water, with purple normally signifying non-potable water and blue indicating potable water. Depending on its intended use, recycled water can be treated so that it is suitable for toilet flushing, landscaping, cooling towers, construction sites or bathing. Although there are standards for different types of fit-for-purpose water in some locations, there is an absence of consensus on the names used for each.

Centralized, Distributed and Decentralized Systems

The terms centralized, distributed and decentralized are often used to describe different approaches to water treatment and management. However, a clear and consistent understanding of these terms is crucial for effective communication and collaboration among stakeholders. For the purposes of this report, the following system framework offers a helpful guide:

Centralized Water Infrastructure: Municipal-scale systems of water supply, sewerage and urban drainage owned and managed by a sole service provider that operates on a municipal or regional basis.

Distributed Water Infrastructure: A system of water supply, water treatment, distribution, sewage collection, treatment and reuse operating at the scale of city districts, commercial offices and multi-family residential buildings. These systems often employ advanced technology to enable space-efficient process intensification and reduce the need for dedicated, on-site staffing.
The recycled water that they produce is usually sent to local users through a dedicated non-potable water distribution system. Distributed systems are usually connected to the municipal water and sewer systems, and are always deployed in collaboration with local water municipalities and utilities. Distributed systems operate in conjunction with centralized water supply and wastewater collection systems rather than independently.

Decentralized Water Infrastructure: A wastewater collection, treatment and water recycling system that serves one building or dwelling at premise-scale (e.g., a single-family home, an individual condominium unit). These systems are usually connected to the municipal water and sewer systems, which provide a fractional water source, as well as potable water for drinking and firefighting. These municipal connections can also supply the premise if the recycling system is taken offline for repairs, and may serve as a means of disposing of residuals (e.g., salts, organic matter) produced by the decentralized recycling system.

Extreme Decentralized Water Infrastructure: A water system capable of meeting all of the water needs of a building or individual premise under most circumstances. Extreme decentralized systems, which are sometimes referred to as net-zero water buildings, employ elements of process intensification and may recycle water at either the individual appliance scale or at the scale of the entire property. These systems, which are designed to operate independently of the centralized water supply and collection system, may benefit from connections to centralized water systems, which can supply them with water during extended droughts or when system components fail. However, with sufficient failsafe measures, they also may be able to operate independently.

In addition to the terms above, water professionals sometimes utilize the terms onsite and hybrid systems. In fact, these terms have been codified into law in the State of California [8]. Onsite systems usually refer to water treatment solutions that are implemented at the location where water is used, such as residential or commercial buildings. This definition does not distinguish between deployment in an individual premise or a district of distinct properties, owners and occupants. These systems typically include graywater recycling and/or rainwater harvesting. The term “hybrid” usually refers to centralized infrastructure operating in concert with the centralized water distribution and wastewater collection system.

Graywater: Definition, Regulation and Acceptable Use

Participants at the workshop provided many helpful insights on graywater, a topic that represents a significant potential water supply in the context of alternative water reuse at non-centralized scale. Estimates suggest that up to 70% of household wastewater production is graywater, but leaves the home as sewage when comingled with toilet and kitchen drain waters (Oteng-Peprah et al. 2018).

One significant challenge identified is that graywater is used as both a technical and colloquial term, with different meaning to different people. On one hand, graywater is often used as a catch-all for wastewaters that do not include sewage generated from toilets. This is a common understanding of the term by the lay public. However, graywater has also been used as a technical term by various entities, which usually describe more detailed assumptions about the sources and quality of this wastewater stream. An additional colloquial term, “hygienic water,” emerged from the workshop as a potential descriptor for wastewaters meeting higher quality than technically defined graywater but not meeting full potable water standards. The development of this term and the concepts behind it could follow a more thorough investigation of the space between commingled and single-source graywaters, and municipally supplied potable water.

Historically, the term “graywater” was coined to represent wastewater with lesser risk of pathogen contamination, typically sourced from non-toilet origins. As knowledge grew, professionals recognized that other water sources within homes and businesses could potentially harbor high levels of pathogens, including but not limited to waters from the kitchen sink or generated from restaurants. This led to the development of various definitions of graywater. In order to understand the full opportunity for the colloquial “graywater” as an alternative supply source, several technical definitions are examined below, along with alternative supply opportunity areas that lie outside of some technical definitions.

8 “Onsite” terminology is codified into California law. See: *https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/onsite_nonpotable_reuse_regulations.html#:~:text=California%20Water%20Code%20section%2013558,%2C%20and%20mixed%2Duse%20buildings.*

Source	Description
Clean Water Act, 33 U.S.C. § 312(a)(11) Table 3-2 ("Legal Information Institute" n.d.)	Defines graywater as water from clothes washing, bathing, dishwashing and sinks (including kitchen) in the context of marine discharge.
California Plumbing Code ("Alternative Water Sources" 2019)	Defines graywater as water from clothes washing and bathing. California law does not allow graywater use from kitchen sinks or dishwashers. Subsurface irrigation with graywater is allowable without treatment.
United States EPA (United States EPA n.d.)	Graywater includes any wash water that has been used in a home or business, except water from toilets. This water is considered to be more reusable, especially for landscape irrigation purposes.
National Academies (National Academies 2016)	Defines graywater as water from bathing, clothes washing, and excludes kitchen waters on the basis of higher levels of solids, organic matter and indicator organisms. Graywater is described as highly variable based on location and contributing source.

Graywater's composition may vary significantly in cleanliness and health risk across applications, spanning a wide range of waste streams as per both colloquial usage and technical definitions. While most definitions envision treating and reusing combined graywater, the growth of decentralized water recycling has necessitated the independent consideration of individual graywater sources and their unique qualities. Graywater derived from individual drains and appliances may have different characteristics than the variable combined sources described above and may include a more predictable water quality. Further research is needed to better characterize these nuances in graywater source qualities for decentralized treatment technologies that are treating individual sources.

Recognizing the distinction between various individual graywater sources, determining their specific water-quality ranges, and identifying the appropriate and efficient treatment for each type is critical for accelerating the adoption of premise-scale water reuse systems. The following table outlines potential research pathways for some individual-drain sourced graywaters:

Graywater sourced from individual drains or appliances	Research opportunity
Shower water	• Water quality characterization and determination of appropriate treatment to enable this alternative supply source • Recirculation for a single user • Recirculation between household users • Characterization of heat recovery potential • Consideration for reuse within other distinct appliances such as washing machines
Bathroom sink	• Water quality characterization and determination of appropriate treatment to enable this alternative supply source • Consideration for in-appliance reuse or use for other bathroom water needs including toilet
Dishwasher	• Water quality characterization and determination of appropriate treatment to enable this alternative supply source
Laundry washing machine	• Water quality characterization and determination of appropriate treatment to enable this alternative supply source

Rethinking Terminology: Potable, Non-potable and Hygienic Water

The current practice in building and premise-scale water systems distinguishes between potable and non-potable water, with non-potable water typically being derived from treated sewage that has undergone filtration and disinfection, as well as treated graywater. As defined by regulations such as Title 22 of the California Code of Regulations, potable water must be used for drinking, cooking and personal hygiene (i.e., in sinks and showers) ("California Office" 2019). Because these uses account for up to half of indoor water use, decentralized systems that aspire to recycle a larger fraction of the wastewater produced in buildings will either have to treat gray- or blackwater to a point at which it meets drinking water standards, or convince regulatory authorities that water produced by less intensive treatment can be used safely for some of these applications.

Potable water

Water quality for potable use has a clear legal and regulatory framework when it is delivered by a centralized water system. However, water from household wells, rainwater harvesting systems and other sources are subject to other regulations. In some parts of the world (e.g., Australia), harvested rainwater can be used for potable purposes, whereas some US states disallow or discourage using rainwater to drink. Some emerging technologies, such as premise-scale atmospheric water generators, have been marked as being capable of providing potable water. However, the detection of high concentrations of toxic contaminants, like aldehydes, raise questions about the safety and reliability of such approaches (Mulchandani et al. 2022). Although these contaminants can be removed by various post-harvesting treatments (e.g., activated carbon), decentralized treatment may require additional research on safety and aesthetic water standards for potable water, as well as reexamination of regulatory approaches.

Non-potable water

Although non-potable water may be derived from a variety of sources and subject to different treatment processes, this category also includes a clear legal and regulatory framework to ensure the protection of public health [9]. Non-potable water may be produced from the treatment of effluent at centralized treatment systems and distributed across a large service area, or it may be produced at the premise scale and used locally. Regardless of the source, strict standards for water quality have been developed to create an additional water supply for a multitude of end uses include irrigation, toilet flushing, clothes washing, cooling towers and industrial processes.

Hygienic Water

As discussed above, an additional classification of water encompassing water that is safe enough to be used for personal hygiene but not treated to the same extent as water that is consumed directly may be appropriate. This standard would recognize that low levels of chemical contaminants, such as arsenic or PFAS, would not pose an unacceptable health risk from incidental ingestion, while acceptable concentrations of pathogens and volatile chemicals (e.g., trihalomethanes) might be somewhat higher than existing drinking water standards. Preliminary research has characterized ingestion and exposure risk to water used when showering, and as that risk is statistically distinct from drinking potable water, there may be opportunity to consider a new water quality standard as technologies emerge that can reliably provide it. This is but one of several scenarios being considered that could unlock additional water supply, process efficiency and "fit-for-purpose" water.

9 See *https://www.epa.gov/water-research/onsite-non-potable-water-reuse-research*

Building on this discussion, participants in the meeting introduced a term of "hygienic water," representing an intermediary water standard that may be appropriate for broader uses than traditionally defined graywater, such as skin contact. The top priority is to prevent infections and illnesses with exposure to treated water. For end uses of toilet flushing and irrigation, exposure is characterized by ingestion of small amounts of water. In decentralized reuse applications, such as recirculating showers, additional risks include incidental ingestion, contact with skin and mucous membranes, as well as inhalation.

Clear water quality and associated health standards for each type of premise or appliance-scale reuse water would provide device and system manufacturers, building owners and managers, and building occupants with clear guidelines in the design, installation and use of water reuse systems.

By refining water quality standards, definitions and categories, stakeholders in the field of decentralized water treatment can better understand and communicate the nuances of various water treatment systems and approaches, ultimately driving innovation and improved water management solutions.

Striking the Right Balance between Protecting Public Health and Enabling Technology Diffusion

In the United States, water systems are subject to a variety of regulations designed to protect public health and the environment. With respect to public health protection, the federal Safe Drinking Water Act and its subsequent amendments are critical to the management of public water supplies. A variety of other public health regulations also are relevant to the design and operation of building- or household-scale water systems. This system of regulations and codes is managed locally, with state and local regulators playing an important role in the implementation and enforcement of these regulations.

The regulatory framework for water systems under the Safe Drinking Water Act was designed for centralized water treatment and distribution systems. Treatment and supply systems that serve small clusters of homes are often regulated by state public health or environmental protection authorities, while individual homes are subject to rules set by local public health authorities and building codes. Many distributed water systems are located within cities and towns with centralized water systems, and are thus operating within systems that are subject to the regulatory system of the state or local authority having jurisdiction. Traditionally, the legal authority to enforce water quality standards stops at the property line (ICC Digital Codes 2017). Thus, decentralized systems that aspire to deliver potable water sourced from recycled water or harvested rainwater might not be subject to the Safe Drinking Water Act. However, building occupants would likely expect the potable water that they receive to meet the same standards as the municipal system that serves other parts of the city. Requiring the operators of premise-scale systems to comply with the Safe Drinking Water Act standards for cities and towns would greatly add to the cost and complexity of the system, likely making this approach infeasible.

Systems that provide non-potable water also must comply with regulations designed to protect public health. Centralized non-potable water recycling systems are typically subject to regulations established at the state level. Compliance with these regulations, such as California Code of Regulations Title 22, entails a rigorous master planning and commissioning process, which increases the cost of the project while simultaneously providing assurance of public health protection (State Water Resources Control Board 2019). Premise-scale systems also require oversight and testing to protect public health, but requiring the same testing regime as those followed by centralized systems would substantially increase project costs.

To foster the spread of premise-scale water recycling systems in a manner that protects public health, a new regulatory paradigm is needed. In San Francisco, the city and county's non-potable reuse ordinance includes water quality standards, oversight and management to protect public health [10]. Furthermore, the National Blue Ribbon Commission (NBRC) for Onsite Non-Potable Water Systems promotes a similar approach to protect public health across the United States. The last decade of work by the NBRC serves as a model for risk analysis and regulatory framework development. However, the current standards and certifications for decentralized, premise-scale reuse systems developed by certification organizations like the National Sanitation Foundation (NSF) and the International Association of Plumbing and Mechanical Officials (IAPMO) are not aligned with the health risk-based standards adopted by San Francisco and the NBRC, leading to a highly fragmented view of public health regulations. This fragmentation creates challenges for water entrepreneurs who are developing innovative solutions for various water reuse loops.

In order to enable new technologies to move forward, clear water quality standards need to be established to protect public health. While doing so, additional considerations, such as the regulatory burden associated with certifying devices, licensed operators and laboratory testing, should be considered.

Currently, there are no national technical committees or manuals of practice that encompass the full spectrum of stakeholders and the diverse range of water treatment technologies in the sub-category of decentralized reuse at premise-scale. By fostering a more inclusive dialogue and collaborative approach, deployment of emerging technologies may occur faster and promote a more competitive market, while also ensuring public health and safety.

Implications for Energy and Greenhouse Gas Emissions

The adoption of decentralized water treatment systems may have significant implications for energy consumption and greenhouse gas emissions. Results from previous studies suggest that distributed systems may result in energy savings at a systems level, especially in places where large amount of energy are used to distribute water from centralized treatment plants (Shehabi et al. 2012). However, distributed treatment systems also consume energy and are subject to diseconomies of scale that result in greater energy consumption to process water. Furthermore, improperly designed and operated recycling systems can release methane and nitrous oxide, which are potent greenhouse gases. Distributed systems also offer opportunities for energy savings through the recovery of heat from wastewater. In-building water systems also might offer distributed opportunities for energy storage. Additional research is needed to assess the systems-level implications of expanding the use of distributed treatment systems.

10 See: *https://www.sfdph.org/dph/eh/Water/nonPotable.asp*

Costs & Financing of Decentralized Systems: Who pays now, who pays later (and who makes money)

The upfront capital costs for developers, property managers and individual homeowners in decentralized treatment represents a new paradigm in the water sector, by shifting the burden away from utility customers and taxpayers. Further efforts to foster the spread of decentralized treatment systems would benefit from considering approaches that are being employed around the world to finance and establish distributed water recycling projects.

For instance, the SFPUC incentivizes and mandates onsite water infrastructure in its urban core. The SFPUC has untaken extensive modeling efforts to understand the hydraulic effects of additional distributed treatment infrastructure across the city, and incentivizes these distributed water systems to be developed in a way that achieves the greatest overall system efficiency without compromising operation of the centralized system. Sydney Water, a state-owned water utility in Australia, has initiated a trial in which the utility will own and operate approximately 30 Hydraloop treatment systems (Harris, 2021). This premise-scale system enables an individual homeowner to recycle graywater at the household scale, reducing indoor water demand by up to 45%. The potential for these systems to provide a less expensive means of addressing water scarcity might motivate water utilities to develop an entirely new line of business, installing and servicing premise-scale systems. Alternatively, cities might create incentives for private companies to act as service providers for decentralized systems.

The need to ensure affordable and equitable access to water services, whether through centralized water infrastructure or decentralized systems, raises questions about how capital outlay should be structured. In the City of Austin, concerns about affordability delayed the imposition of building-scale treatment mandates in multi-family units. It is crucial to ensure that the benefits of premise-scale systems are available to all citizens irrespective of wealth, and that the costs of adapting water services to increasing scarcity are apportioned in an equitable manner.

Measuring cost-effectiveness can be challenging, given the tendency of centralized water systems to receive revenue from various sources. The cost of adapting water systems to the effects of climate change must be considered. If distributed and decentralized systems become more popular, centralized systems might face challenges in collecting sufficient revenue to maintain the infrastructure. This might lead to a need to increase the connection costs paid by these new water systems or to reconsider the use of volumetric charges in water pricing.

While toilet flushing is currently one of the main uses of recycled water in residential and commercial buildings, opportunities for expansion to water for personal hygiene, whole-home graywater systems and the use of rainwater as a drinking water source – all of which require additional research and development – appear to be attractive targets.

KEY FINDINGS AND RECOMMENDATIONS

Key Findings

This workshop yielded several important observations that could influence future activities related to the further spread of centralized alternatives, including both distributed and decentralized recycling:

- Both distributed and decentralized water recycling systems aim to provide a safe, affordable source of water that minimizes pollution, reduces energy use and reduces the reliance on centralized water systems that are increasingly unreliable.
- The regulatory and professional communities have not yet reached a consensus on approaches for regulating decentralized systems, with system operators often indicating that the regulatory burden of compliance hinders their ability to compete. Regulatory approaches are inconsistent among locations.
- The costs and financing of distributed and decentralized systems present new challenges and opportunities, with different models emerging from around the world.
- In "protected spaces" around the world, decentralized water systems are employing different business models and technologies.
- The attractiveness of both decentralized and distributed recycling systems is influenced by a range of factors, including the community value of water, infrastructure capacity, local energy prices and perceived sustainability benefits.
- The cost, reliability and ease of permitting of decentralized water treatment systems and infrastructure are likely to change as experience is developed by early adopters, service providers and regulators.
- Alternatives to centralized water systems, including distributed and decentralized recycling systems, can feasibly reduce water usage by 25-50% in new and retrofit buildings using existing technology. The development of recycling technologies that expand the possible uses of recycled water could increase the fraction of water that can be recycled.
- Decentralized treatment technologies may enable the future development of true net-zero water buildings

Recommendations

In light of the diverse challenges and opportunities associated with centralized alternatives, it is important to consider various recommendations that can help facilitate their successful adoption and implementation. While each case is unique, there are some overarching suggestions that may prove beneficial across different situations.

1. Standardize definitions and terminology: Develop agreed upon, standardized definitions and terminology for centralized, distributed, decentralized and extreme decentralized water treatment systems, using established frameworks. This will help create a shared understanding among stakeholders, and streamline the development and implementation of new technologies and systems. Until an industry consensus is achieved, define the distributed meaning of this terminology when it is first mentioned.

2. Develop a better understanding of barriers and opportunities for decentralized water treatment systems: Conduct further research on the drivers for change that will enable the spread of decentralized water recycling systems, focusing on the intersection of environmental, economic, technological and societal factors. Understanding these drivers will help policymakers and industry stakeholders identify opportunities for growth and innovation in the decentralized water treatment sector. The market opportunity for technologies in this category needs to be defined in more detail.

3. Develop clear value proposition frameworks for decentralization. Relevant questions include: When, where, how, and for whom does decentralized reuse deliver value? How long is required for return on investment? Will costs associated with the operation of decentralized systems be borne by other community members? While initial purchase costs of onsite systems are well defined and easily tracked, there is little understanding of long-term maintenance and operation costs of the user, utility bills of the end user or revenue opportunities for the end user. There is similarly little quantification of the value proposition for utilities, including the avoided costs of infrastructure investments (piping, marginal supply capacity), the change in operational costs with changing water quality and reduced flow rates, or the change in revenue from water and wastewater service provision.

4. Prioritize research to address key knowledge gaps: Relevant topics include understanding the efficacy of different treatment trains for fit-for-purpose water; enhancing the benefits of sensors, actuators and real-time controls in system operation and water quality monitoring; and development of optimal treatment trains. By investing in targeted research, policymakers and industry stakeholders can make informed decisions about the implementation of decentralized systems and ensure their effectiveness and efficiency.

Photo Credit: aaron007, iStock

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