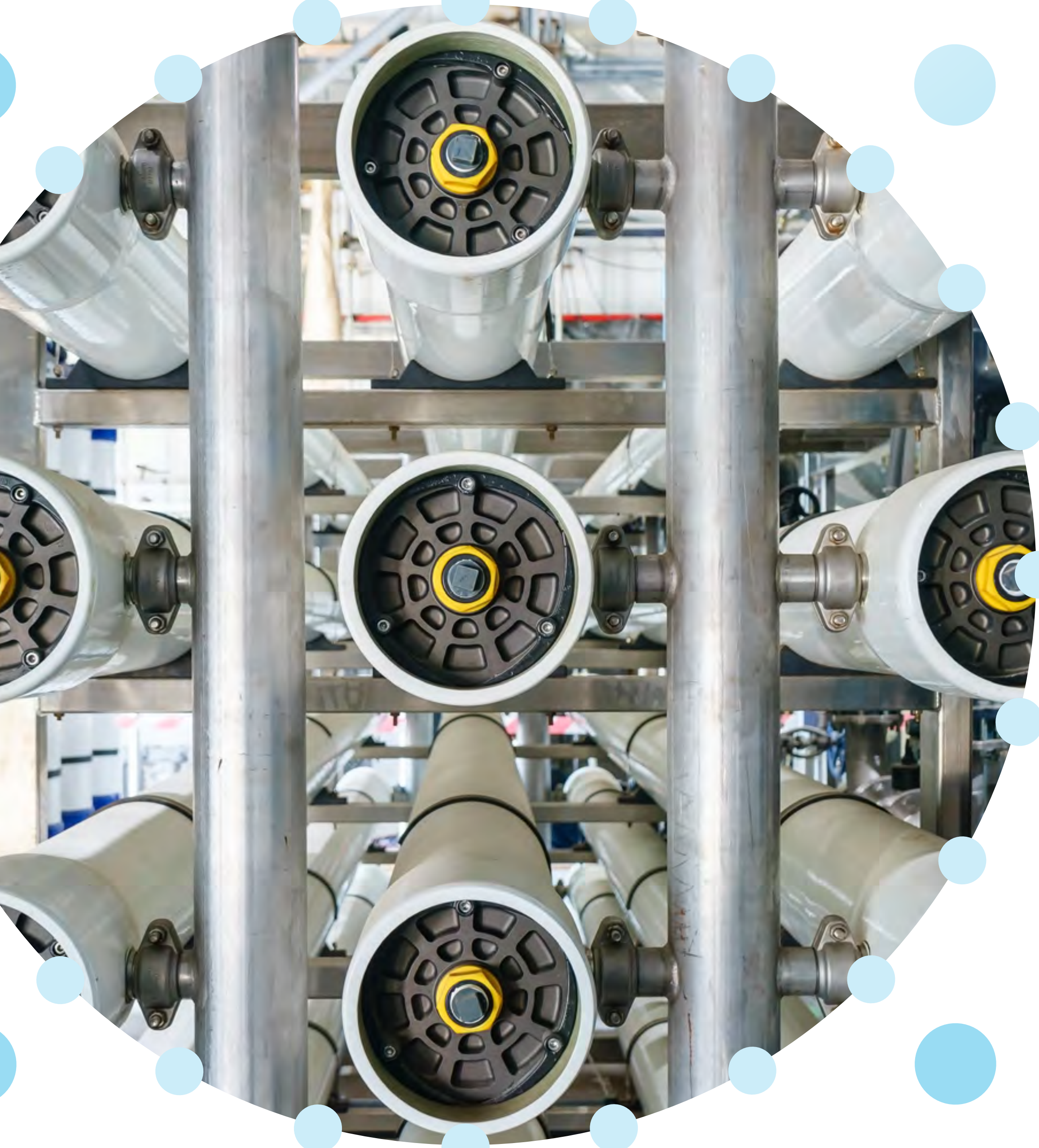
NAWI

National Alliance for Water Innovation

MUNICIPAL SECTOR

TECHNOLOGY ROADMAP



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This report, originally published in May 2021, has been revised in July 2021 to:

- Add authors Thiloka Edirisooriya, Wenbin Jiang, Lu Lin, and Xuesong Xu
- Change a sentence on page 25 to read "...provides approximately 35 percent of their service area's groundwater replenishment needs."
- Correct grammatical errors
- Added new and deleted unused acronyms (Appendix A)
- Renumbered end note citations in sequential order throughout document

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1. EXECUTIVE SUMMARY

1.1 Introduction to NAWI and the NAWI Roadmap

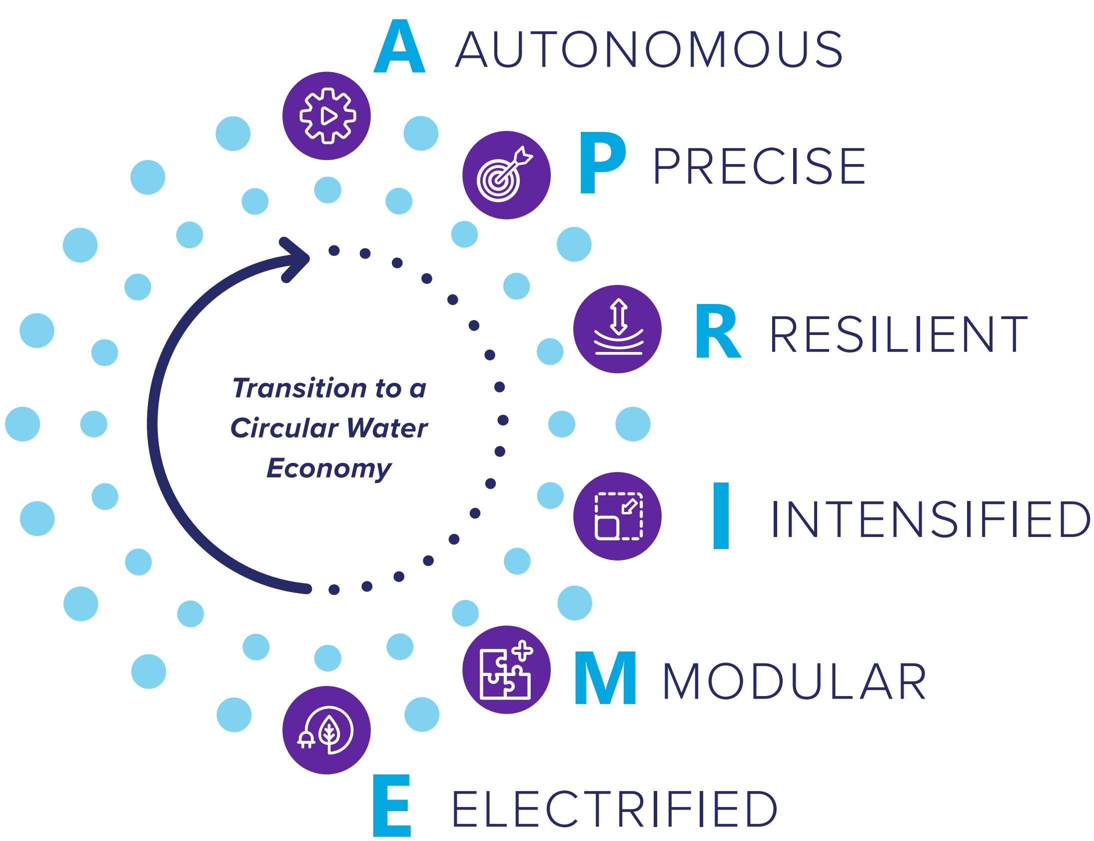
The National Alliance for Water Innovation (NAWI) is a research consortium formed to accelerate transformative research in desalination and treatment to lower the cost and energy required to produce clean water from nontraditional water sources and realize a circular water economy.

NAWI's goal is to ***enable the manufacturing of energy-efficient desalination technologies in the United States at a lower cost with the same (or higher) quality and reduced environmental impact for 90 percent of nontraditional water sources within the next 10 years.***

The nontraditional source waters of interest include brackish water; seawater; produced and extracted water; and power, mining, industrial, municipal, and agricultural waste waters. When these desalination and treatment technologies are fully developed and utilized, they will be able to contribute to the water needs of many existing end-use sectors. **NAWI has identified five end-use sectors that are critical to the U.S. economy for further exploration: Power, Resource Extraction, Industry, Municipal, and Agriculture (PRIMA).**

This **Municipal Sector Roadmap** aims to advance desalination and treatment of nontraditional source waters for beneficial use in public water supplies by identifying research and development (R&D) opportunities that help overcome existing treatment challenges.

Under NAWI's vision, the transition from a linear to a more **circular water economy** with nontraditional source waters will be achieved by advancing desalination and reuse technologies in six key areas: Autonomous, Precise, Resilient, Intensified, Modular, and Electrified, collectively known as the **A-PRIME** challenge areas.

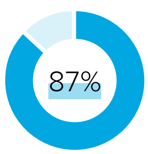


Technological advances in these different areas will enable nontraditional source waters to achieve pipe-parity with traditional supplies.

Pipe-parity is defined as the combination of technological solutions and capabilities (e.g., resiliency enablers and strategies leading to long-term supply reliability) and non-technological solutions that make marginal water sources competitive with traditional water resources for specific end-use applications.

To effectively assess technology advances and capabilities, NAWI will use pipe-parity metrics relevant for the Municipal End-Use Sector. These metrics can be quantitative or qualitative, depending on how an end user would evaluate different potential water sources and whether they could be integrated into their supply mix.

1.2 Water User Sector Overview



Total withdrawals for public supply, referred to as municipal uses in this roadmap, were about 148 million cubic meters (m^3) per day (or 39 billion gallons per day) in 2015, delivering potable water to about 87 percent of the U. S. population.

The primary sources of water for municipal use are surface and groundwater supplies, with the majority of water drawn from fresh surface-water sources. Although some municipalities use nontraditional waters (especially in water-stressed regions), financial, regulatory, and other challenges affect the utilities' decisions to treat and distribute nontraditional water sources further.

As the U.S. population grows and shifts geographically and climate change impacts water supplies, nontraditional source waters will need to play a bigger role in meeting water supply demands.

1.3 Water Treatment and Management Challenges

Table 1 identifies broad industry challenges and key gaps that need to be addressed to enable the Municipal Sector to efficiently use nontraditional source waters. These barriers have been identified through workshops and discussions with subject matter experts, as part of a structured roadmapping process. The barriers are too large and far-reaching for any one organization to solve on its own. NAWI intends to invest in promising research at technology readiness levels (TRLs) 2–4 that are cross-cutting the PRIMA areas. The new technologies are to address some of the challenges discussed below, and NAWI welcomes complementary efforts by other research organizations.

Table 1. Synopsis of technical and non-technical challenges to utilizing nontraditional water sources for the Municipal Sector

TECHNICAL

System Durability and Compatibility

- Treatment systems configured for nontraditional water sources may not be capable of handling constituents not normally found in traditional water supplies or flexible enough to withstand rapidly changing influent qualities.
- Aging infrastructure, existing premise plumbing, and water bodies receiving effluent discharge may not be compatible with nontraditional water supplies.

Monitoring and Detection Limitations

- The technologies needed for real-time or near real-time performance monitoring and feedbacks in municipal treatment systems are inadequate and/or too expensive, particularly for small-scale applications.
- There is a lack of standard methods that can detect the broad range of detrimental constituents entering or exiting the water treatment system, and existing data collection and analytical tools are too costly for frequent monitoring.
- Municipal systems currently lack tools to rapidly validate the treatment efficiency for removal of specific constituents and evaluate long-term toxicological risks associated with utilizing alternative source waters.

Inefficient System Designs

- Desalination and water reuse treatment processes are typically performed at large, centrally located facilities that require substantial amounts of energy for water distribution; smaller distributed systems can minimize distribution transport costs but can be cumulatively more expensive per unit of water production.
- Intermittent flow and fluctuating quality of nontraditional waters complicate system operations, potentially impacting the quality of delivered water and system performance.

TECHNICAL

Residuals Management

- Municipal water treatment systems have constrained options for managing residuals; the use of nontraditional waters may be limited by feasible disposal options for residuals, especially concentrate streams from reverse osmosis.

Workforce, Materials, and Equipment Development

- The use of nontraditional water sources for municipal water production will require the adoption of new treatment technologies, monitoring and control methods, and overall management strategies. However, a workforce capable of operating and maintaining complex new technologies is in shortage to keep pace with these innovations.
- Materials and equipment currently used for treating traditional source waters are sensitive to corrosion, fouling, and failures when exposed to high-salinity and high-organic water sources.

NON-TECHNICAL

- Implementing new technologies often comes with significant costs for early adopters due to higher risks of failure and more expensive design, capital, verification, and/or operating costs.
- Some utilities hesitate to embrace the use of alternate water sources due to perceived concerns regarding public health, potential loss of revenue, and diversion of treated wastewater currently meeting downstream water user and ecological needs.
- Different rules, regulations, and laws stemming from local, state, and federal jurisdictions create challenges for developing technology solutions for using nontraditional water sources in municipal water systems across different regions.
- Providing distributed fit-for-purpose treatment as a means of more efficiently and cost-effectively managing urban water infrastructure requires engagement and agreement among diverse stakeholders.

1.4 Research Priorities

To overcome these industry challenges, strive towards meeting pipe-parity, and achieve NAWI's mission of expanding the use of nontraditional source waters for the Municipal Sector, this roadmap lays out several research priorities that were identified through structured roadmapping processes with subject matter experts. These R&D Areas of Interest (AOIs) are grouped under the individual A-PRIME categories discussed earlier. Specific research gaps— technologies or problems that have not been sufficiently answered by existing studies—are also included with each priority area. At the end of this summary of topics, a short discussion of the benefits of new technoeconomic analysis and life cycle analysis research is provided.

The Autonomous area entails developing robust sensor networks coupled with sophisticated analytics and secure controls systems.
Specific prioritized research areas include:

- **Develop continuous or near real-time sensors for pathogens to prioritize acute impacts and routine monitoring of carcinogens and contaminants of emerging concern (CEC) removal for municipal wastewater reuse.** Adoption of alternative sources of water to meet municipal water demands is challenged by the various impurities and constituents in nontraditional sources of water. Portable, rapid, low-cost, and easy-to-use sensors could also promote localized water reuse (e.g., at the building scale) by offering rapid results with minimal technical training.

- **Develop new approaches for remotely verifying the performance and safety of building-scale and point-of-use treatment systems.** Point-of-use treatment units for small water systems need to be made more modular with sensors that enable remote monitoring of performance. Realizing these capabilities could break through regulatory and ownership barriers to implementation as components of a public water system.

- **Create sensors or sensor arrays that can report the propensity of fouling and inorganic scaling.** Reverse osmosis (RO) membrane fouling (including biofouling) and scaling increase the cost of treatment. Rapid detection of constituents that contribute to scaling and fouling could allow adjustment of treatment or pre-treatment technologies to prevent system failures. Improved real-time monitoring would ensure the proper function and lifespan of water treatment plant equipment and distribution systems.

- **Develop capabilities to drive more autonomous operation of treatment plants.** Current water treatment operation requires well-trained engineers and experienced operators to perform routine checkups on the plant. The current operation is not only demanding on human resources, but it also has the potential to introduce errors due to the delay of data and the involvement of human decision on the operation. A digital revolution using artificial intelligence enables prediction of water quality inputs and system operation to predict output water quality.

The Precise area focuses on a targeted treatment approach with precise removal or transformation of treatment-limiting constituents and trace contaminants. Specific research areas include:

- **Develop technology and engineered materials for selective adsorption, destruction, or separation of target constituents and in situ regeneration of selective capturing sites on engineered material surfaces.** Current water treatment technologies are effective for removal of most particles, bulk organics, and solutes. However, certain types and concentrations of constituents in alternative sources of water supply present significant challenges to the current water treatment industry. Precision separation of hard-to-treat water constituents (e.g., oxyanions, organic contaminants) either during pre-treatment, treatment, or post-treatment could significantly improve water treatment efficiency, which could lower the overall energy demand and cost of the process.

- **More effectively harness microbial accelerated engineering technologies for removal of nutrients, organic compounds (e.g., CECs, biofouling constituents), and minerals.** Biological treatment has been an important process to remove bulk organic carbon from wastewater. However, there are weaknesses in its ability to remove nutrients and trace organic contaminants. The development of more effective biological treatment methods, especially in the presence of elevated concentrations of salt, has the potential to improve the performance of systems that produce municipal water from wastewater, seawater, and brackish water.

The Resilient area looks to enable adaptable treatment processes and strengthen water supply networks. Specific research areas include:

- **Improve materials and surface capabilities and develop effective pre-treatment processes for reduction of fouling, scaling and corrosion.** With greater use of nontraditional source waters, especially municipal wastewater and seawater, influent composition to a facility can vary diurnally, episodically (e.g., when it rains), seasonally (e.g., during algal blooms), and over years (e.g., through conservation efforts). For the small-scale water treatment systems envisioned by NAWI, these fluctuations will likely be more extreme than those encountered at large, centralized treatment plants. New materials, process engineering, and fundamental science will allow water systems to become more resilient to variations in water supply, operations, and finished water quality.

- **Design new materials that have longer lifetimes and are easier for reuse, remanufacture, or recycle.** Replacement of treatment components represents significant operating and maintenance costs that could be lowered by increasing the lifetimes of treatment components. New materials and process engineering designs will lead to equipment and systems with increased lifetimes. Incorporation of the reuse, remanufacture and recycle feature in the new material design will further lower the life cycle cost of the water treatment facility.

- **Improve mechanistic understanding of physical, chemical, and biological characteristics and interactions of treated nontraditional water with other source water during blending and with existing distribution and storage infrastructure.** Water quality can become degraded during distribution and storage as a result of metal corrosion, biofilm formation and sloughing, growth of opportunistic pathogens, and generation of disinfection byproducts. Developing knowledge to mitigate corrosion and biological growth during blending, distribution and storage could maintain product water quality.

- **Advance understanding of fundamental mechanisms of fouling, scaling, and corrosion.** The underlying physical, chemical, and biological aspects of the phenomena of fouling, scaling, and corrosion have been studied for decades, but there are knowledge gaps regarding alternative water chemistries and the implications of these processes at multiple spatial scales. Research that advances fundamental nucleation and crystal growth and microbial ecology of biofilm formation at conditions relevant to water treatment and supply can provide a bridge between basic interfacial science and early-stage water treatment research and development.

The Intensified area focuses on innovative technologies for brine concentration and crystallization and the management and valorization of residuals. Specific research areas include:

- **Develop innovative technologies to reduce the volume of concentrate for disposal, achieve near zero-liquid discharge (ZLD), and couple brine management with resource recovery.** Brine management is a significant challenge for implementing and expanding brackish water desalination and water reuse for municipal applications, especially in inland areas where concentrate disposal options are limited. With advances in desalination, it may be possible to extract valuable minerals, nutrients, and other chemicals from concentrate while simultaneously increasing product water yields. Resource recovery and volume reduction also reduce disposal cost and can create revenue from commercial product sales.

- **Develop advanced geochemical modeling and in operando monitoring tools to characterize precipitation, nucleation, crystallization, solute activity, and heat transfer in high-salinity waters.** Brines contain high levels of salts that can cause scaling and corrosion in treatment units, equipment, and pipelines. Current aqueous solution models have limited ability to accurately predict precipitation kinetics under a wide range of temperatures and pressures and in the presence of organics and microbiological components typical of brine streams. Using in operando monitoring tools and developing advanced geochemical or biogeochemical models to predict chemical change, speciation, and precipitation could significantly improve the performance of brine management systems.

The Modular area looks to improve materials and manufacturing processes to expand the range of cost-competitive treatment components and eliminate intensive pre/post-treatment. Specific research areas include:

- **Develop manufacturing innovations for on-demand production of water treatment system components.** Operations and maintenance (O&M) of municipal water systems have cost and efficiency challenges associated with the site-specific aspects of many of their designs. In addition to posing challenges of costs and operational efficiencies, unique designs and the wide range of scales of treatment systems also increase the complexity of regulatory approval and maintenance. Developing modular units offers the opportunity to take advantage of economies of scale in manufacturing to lower costs of water production for small-scale systems. The emergence of additive and advanced manufacturing technologies has the potential to shorten supply chains and lower operating and maintenance costs of treatment facilities.

- **Advance technologies that can improve the performance of building-scale water treatment and reuse systems.** Currently, the technologies for reliable operations of the microbial community in bioreactors for organic waste removal and the understanding of corrosion control and biofilm growth in building-scale water distribution are limited. Advances using demonstration-scale systems are also needed.

The Electrified area aims to replace chemically intensive processes with electrified processes that are more amenable to variable or fluctuating operating conditions. Specific research areas include:

- **Develop innovative technologies and materials to improve system efficiency and reduce the costs and energy demand of electrified processes.** Water treatment and desalination are chemically intensive processes that consume large quantities of chemicals for routine O&M. Replacing chemical processes with electrical inputs can promote small-scale, distributed water treatment by reducing the need for a chemical supply and minimizing the complexity of water treatment operations. Membrane-based processes are inherently electricity-driven, and electrosorption, electrocatalysis, and electrocoagulation can use electricity to enhance selectivity and other metrics of treatment performance.

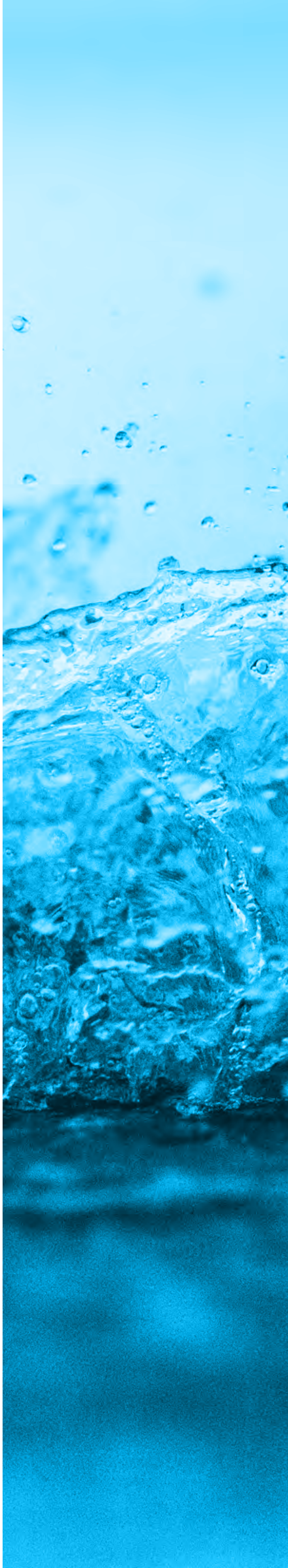
- **Evaluate electrified processes through on-site monitoring, modeling, and material innovations.** The mechanisms that determine how certain electrified processes work and, more importantly, the underlying complex physicochemical mechanisms involved in their application to water treatment processes, are not fully understood. Advances in electrified processes hold promise for energy-efficient, environmentally friendly, modular alternatives to traditional chemical treatment methods.

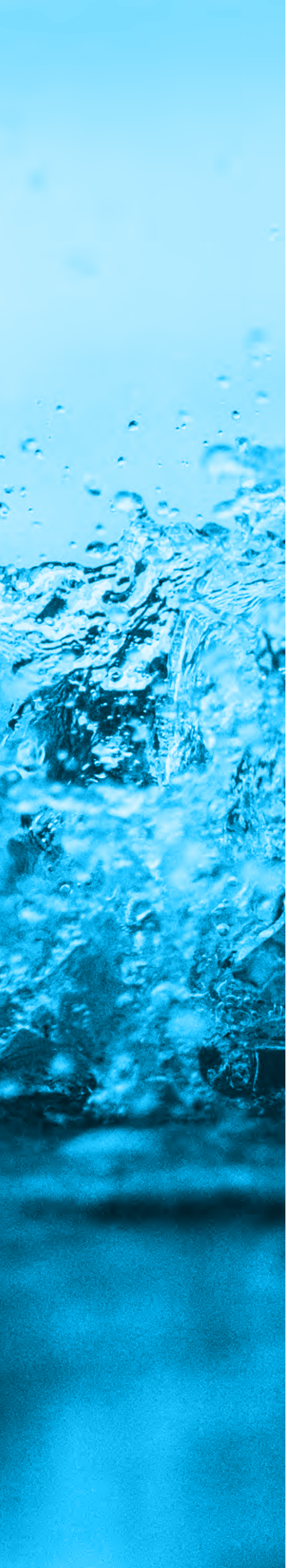
- **Incorporate variable renewable energy into water treatment systems and leverage clean energy to replace chemical-intensive systems with electricity-intensive systems.** While water treatment processes have traditionally been designed to operate continuously, integration with demand response electricity markets or direct powering with variable renewable energy sources will require treatment systems that can also be operated flexibly with quick ramping capabilities. Replacing chemically intensive processes with electrified processes provides a means of exploiting a variety of renewable and clean energy resources and temporal variations in electricity costs.

Technoeconomic analysis and life cycle analysis opportunities: Improving the economic viability of treatment systems that can treat to the level needed for municipal applications could enable a transition to advanced treatment technologies for other end-use applications.

Incorporating a systems-level approach when evaluating new technologies through technoeconomic analysis (TEA) and life cycle assessment (LCA) strengthens the argument for research investment in low TRL water treatment approaches. The previously discussed research needs could be augmented with the following TEA and LCA studies:

- **Evaluate** the technical and economic feasibility (including market and demand investigation), process efficiency, resilience, robustness, product purity, environmental benefits, and potential risks of failure for intensified brine processes.
- **Conduct** TEA and LCA of electrified treatment for different water quality characteristics, operating conditions, locations, and scales (e.g., centralized vs. decentralized, municipal vs. rural/remote locations). These assessments can examine energy sources, chemical products generated, technologies used, safety concerns, and risks of handling hazardous chemicals.
- **Quantify** the potential benefits of new materials with longer lifetimes or easier reuse and recycle.
- **Quantify** the costs and benefits of advanced manufacturing processes for the production of water treatment components.
- **Assess** the potential for sensor-enabled and remotely controllable modular point-of-use treatment units for small water systems to break through regulatory and ownership barriers to implementation as components of a public water system.
- **Evaluate** the value proposition of developing disposable sensors for the municipal water supply industry.
- **Quantify** the synergies between renewable energy and electrified water treatment as well as the benefits gained in stability, reliability, and flexibility derived from electrification.





1.5. Next Steps

NAWI's comprehensive and dynamic roadmap for desalination and water treatment technologies for the Municipal End-Use Sector is intended to guide future R&D investments throughout the duration of the research program. Because this roadmap forecasts into the future and is meant to guide NAWI throughout its existence, it should be considered a living document that is periodically re-evaluated and revised to ensure its continued relevancy. With ongoing input from industry stakeholders and support from academia, water utilities, water professionals, and other NAWI partners, the Alliance will update this roadmap to ensure it evolves to capture progress of high-priority objectives as well as the emergence of new technologies.

1.6. Appendices

The appendices include a list of relevant acronyms for this document (Appendix A); an expanded description of the NAWI A-PRIME hypothesis (Appendix B); Department of Energy (DOE) Water Hub development background (Appendix C); roadmap teaming structure (Appendix D); in-depth examination of the roadmap development process (Appendix E); technology roadmap contributors (Appendix F); and relevant references (Appendix G).

2. INTRODUCTION

2.1. Growing Challenges with Water

Clean water is critical to ensure good health, strong communities, vibrant ecosystems, and a functional economy for manufacturing, farming, tourism, recreation, energy production, and other sectors' needs.[1]

Water managers in 40 states expect water shortages in some portion of their state in the next several years.[2] As water insecurity grows in severity across the United States and populations increase in regions with limited conventional sources, using water supplies traditionally ignored or avoided due to treatment challenges are being reconsidered.

Research to improve desalination technologies can make nontraditional sources of water (i.e., brackish water; seawater; produced and extracted water; and power sector, industrial, municipal, and agricultural wastewaters) a cost-effective alternative. These nontraditional sources can then be applied to a variety of beneficial end uses, such as drinking water, industrial process water, and irrigation, expanding the circular water economy by reusing water supplies and valorizing constituents we currently consider to be waste.[3] As an added benefit, these water supplies could contain valuable constituents that could be reclaimed to further **a circular economy.**

2.2. Establishing an Energy-Water Desalination Hub

In 2019, DOE established an Energy-Water Desalination Hub (part of a family of Energy Innovation Hubs[4]) to address water security issues in the United States. NAWI was funded to address this critical component of DOE's broader Water Security Grand Challenge to help address the nation's water security needs. NAWI's goal is to ***enable the manufacturing of energy-efficient desalination technologies in the United States at a lower cost with the same (or higher) quality and reduced environmental impact for 90 percent of nontraditional water sources within the next 10 years.***

NAWI is led by Lawrence Berkeley National Laboratory in Berkeley, California and includes Oak Ridge National Laboratory, the National Renewable Energy Laboratory, the National Energy Technology Laboratory, 19 founding university partners, and 10 founding industry partners. This partnership is focused on conducting early-stage research (TRLs 2–4) on desalination and associated water-treatment technologies to secure affordable and energy-efficient water supplies for the United States from nontraditional water sources. NAWI's five-year research program will consist of collaborative early-stage applied research projects involving DOE laboratories, universities, federal agencies, and industry partners. DOE is expected to support NAWI with $110 million in funding over five years, with an additional $34 million in cost-share contributions from public and private stakeholders.

As a part of the NAWI research program, this strategic roadmap was developed for the Municipal Sector to identify R&D opportunities that help address their particular challenges of treating nontraditional water sources. Recognizing the important sector-specific variations in water availability and water technology needs, NAWI has also published four other end-use water roadmaps, each with specific R&D and modeling opportunities (power, resource extraction, industry, and agriculture). Each roadmap has been published as a standalone document that can inform future NAWI investments as well as provide insight into priorities for other research funding partners.

2.3. Pipe-parity and Baseline Definitions

A core part of NAWI's vision of a circular water economy is reducing the cost of treating nontraditional source waters to the same range as the portfolio of accessing new traditional water sources, essentially achieving pipe-parity. The costs considered are not just economic but include consideration of energy consumption, system reliability, water recovery, and other qualitative factors that affect the selection of a new water source. To effectively assess R&D opportunities, pipe-parity metrics are utilized; they encompass a variety of information that is useful to decision makers regarding investments related to different source water types.

Pipe-parity is defined as technological and non-technological solutions and capabilities that make marginal water sources viable for end-use applications. Like the concept of grid parity (in which an alternative energy source generates power at a levelized cost of electricity [LCOE] that is less than or equal to the price of power from the electricity grid), a nontraditional water source achieves pipe-parity when a decision maker chooses it as their best option for extending its water supply.

Specific pipe-parity metrics of relevance can include:

Cost	Cost metrics can include levelized costs of water treatment as well as individual cost components, such as capital or O&M costs.
Energy Performance	Energy performance metrics can include the total energy requirements of the water treatment process, the type of energy required (e.g., thermal vs. electricity), embedded energy in chemicals and materials, and the degree to which alternative energy resources are utilized.
Water Treatment Performance	Water treatment performance metrics can include the percent removal of various contaminants of concern and the percent recovery of water from the treatment train.
Human Health and Environment Externalities	Externality metrics can include air emissions, greenhouse gas emissions, waste streams, societal and health impacts, and land-use impacts.
Process Adaptability	Process adaptability metrics can include the ability to incorporate variable-input water qualities, the ability to incorporate variable-input water quantity flows, the ability to produce variable-output water quality, and the ability to operate flexibly in response to variable-energy inputs.

Reliability and Availability

System reliability and availability metrics can include factors related to the likelihood of a water treatment system not being able to treat water to a specified standard at a given moment, how quickly the system can restart operations after being shut down for a given reason, confidence in source water availability, the degree to which the process is vulnerable to supply chain disruptions, and the ability to withstand environmental, climate, or hydrological disruptions.

Compatibility

Compatibility metrics can include ease of operation and level of oversight needed, how well the technology integrates with existing infrastructure, how consistent the technology is with existing regulations and water rights regimes, and the level of social acceptance.

Sustainability

Sustainability metrics can include the degree to which freshwater inputs are required for industrial applications, the percentage of water utilized that is reused or recycled within a facility, and watershed-scale impacts.

To establish references on which pipe-parity metrics are most applicable in each sector, **baseline studies** for each of NAWI's eight nontraditional water sources have been conducted. These studies collect data about the use of each source water and evaluate several representative treatment trains for the targeted source water to better understand current technology selections and implementation methods. The baselines provide range estimates of the current state of water treatment pathways across pipe-parity metrics, which enable calculation of potential ranges of improvement.

Specific baseline information required includes:

a. Information on the type, concentration, availability, and variability of impurities in the source water
b. Identification of key unit processes and representative treatment trains treating the source water and their associated cost, removal efficiency, energy use, robustness, etc.
c. Ranges of performance metrics for treatment of the source water for applicable end-uses
d. Definitions of pipe-parity for the source water type and water use

2.4. Nontraditional Waters of Interest

2.4.1. Sources of Nontraditional Waters

NAWI has identified eight nontraditional water supplies of interest for further study (Figure 1):

Seawater and Ocean Water	Water from the ocean or from bodies strongly influenced by ocean water, including bays and estuaries, with a typical total dissolved solids (TDS) between 30,000 and 35,000 milligrams per liter (mg/L).
Brackish Groundwater	Water pumped from brackish aquifers with particular focus on inland areas where brine disposal is limiting. Brackish water generally is defined as water with 1,000 to 10,000 mg/L TDS
Industrial Wastewater	Water from various industrial processes that can be treated for reused
Municipal Wastewater	Wastewater treated for reuse through municipal resource recovery treatment plants utilizing advanced treatment processes or decentralized treatment systems
Agricultural Wastewater	Wastewater from tile drainage, tailwater, and other water produced on irrigated croplands as well as wastewater generated during livestock management that can be treated for reuse or disposal to the environment
Mining Wastewater	Wastewater from mining operations that can be reused or prepared for disposal
Produced Water	Water used for or produced by oil and gas exploration activities (including fracking) that can be reused or prepared for disposal
Power and Cooling Wastewater	Water used for cooling or as a byproduct of treatment (e.g., flue gas desulfurization) that can be reused or prepared for disposal

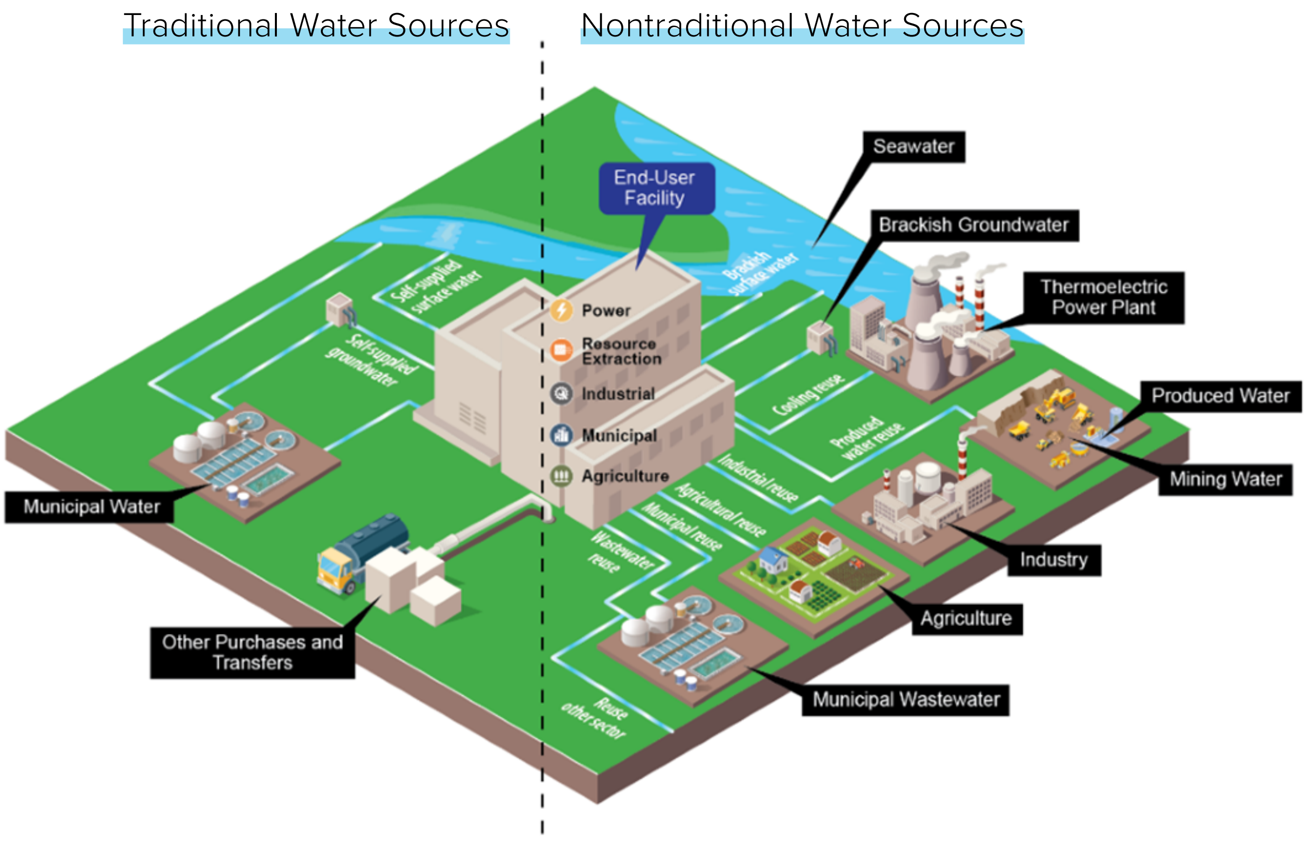


Figure 1. Schematic of traditional and nontraditional sources of waters, as defined by NAWI

(Graphic courtesy of John Frenzl, NREL)

These water sources range widely in TDS (100 mg/L – 800,000 mg/L total) as well as the type and concentrations of contaminants (e.g., nutrients, hydrocarbons, organic compounds, metals). **These different water supplies require varying degrees of treatment to reach reusable quality.**

2.4.2. End-Use Areas Using Treated Nontraditional Source Waters

When these nontraditional water supplies are treated with novel technologies created through the NAWI desalination hub, these remediated wastewaters could be repurposed back to one or more of the following five end-use sectors.

Power	Water used in the electricity sector, especially for thermoelectric cooling
Resource Extraction	Water used to extract resources, including mining and oil and gas exploration and production
Industrial	Water used in industrial and manufacturing activities not included elsewhere, including but not limited to petrochemical refining, food and beverage processing, metallurgy, and commercial and institutional building cooling
Municipal	Water used by public water systems, which include entities that are both publicly and privately owned, to supply customers in their service area
Agriculture	Water used in the agricultural sector, especially for irrigation and food production

NAWI identified these broad "PRIMA" sectors because they are major users of water with opportunities for reuse. Figure 2 expands on the industries included in NAWI's PRIMA broad end-use sectors. These areas are not meant to be exhaustive, as nearly all industries and sectors rely on water in one way or another.

END-USE SECTOR	INDUSTRIES INCLUDED
Power	Thermoelectric Renewable energy
Resource Extraction*	Upstream oil and gas Hydraulic fracturing operations Mining
Industrial†	Refineries Petrochemicals Primary metals Food and beverage Pulp and paper Data centers and large campuses
Municipal	Public supply for use by residential, commercial, industrial, institutional, public service, and some agricultural customers within the utility service area
Agriculture	Irrigation Livestock Upstream food processing

Figure 2. PRIMA and the industries covered in each area

2.5 A-PRIME

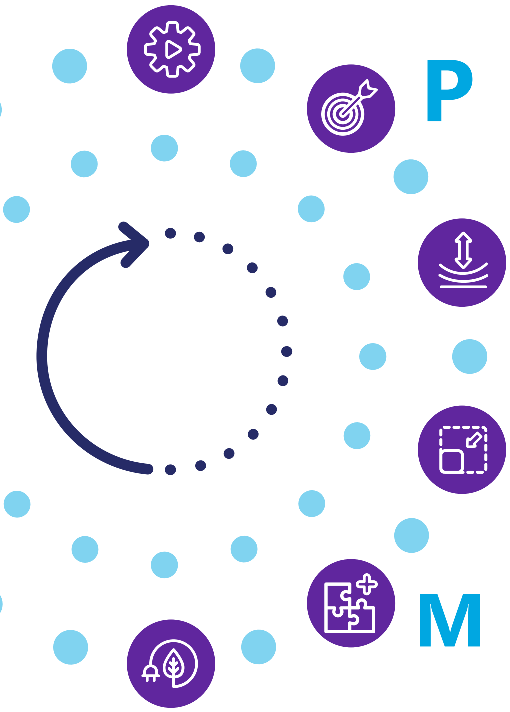
Securing water supplies for multiple end-uses requires technology revolutions that will transition the United States from a linear to a circular water economy.

These desalination and reuse advances will be realized by developing a suite of Autonomous, Precise, Resilient, Intensified, Modular, and Electrified (A-PRIME) technologies that support distributed and centralized treatment at a cost comparable to other inland and industrial sources.[3] Each aspect of this hypothesis has been vetted with water treatment professionals from each PRIMA industry sector as well as NAWI's Research Advisory Council (RAC) to ensure that it is a relevant means of advancing desalination and water treatment capabilities for nontraditional source waters. These areas may be modified as new priorities and opportunities are identified.

* An important distinction for oil and gas and mining operations: upstream drilling operations fall under the Resource Extraction Sector and downstream refining operations fall under the Industrial Sector.

† This list of industries for the Industrial Sector is for baselining and initial roadmapping. This list will be reviewed in future roadmap iterations.

The NAWI A-PRIME hypothesis outlines the following six major challenge areas needing improvement for water treatment to reach pipe-parity for nontraditional waters. An A-PRIME synopsis is provided below; a more in-depth discussion on the A-PRIME challenge areas can be found in Appendix B.



A The **Autonomous** area entails developing robust sensor networks coupled with sophisticated analytics and secure controls systems.

P The **Precise** area focuses on a targeted treatment approach with precise removal or transformation of treatment-limiting constituents and trace contaminants.

R The **Resilient** area looks to enable adaptable treatment processes and strengthen water supply networks.

I The **Intensified** area focuses on innovative technologies and process intensification for brine concentration and crystallization and the management and valorization of residuals.

M The **Modular** area looks to improve materials and manufacturing processes and scalability to expand the range of cost-competitive treatment components and eliminate intensive pre/post-treatment.

E The **Electrified** area aims to replace chemically intensive processes with electrified processes that are more amenable to variable or fluctuating operating conditions.

2.6. Desalination Hub Topic Areas

There are key technology areas of R&D, modeling, and analysis that cut across the water sources and sectors in the NAWI Hub.

They can be categorized under four interdependent topic areas, as summarized below:

Process Innovation and Intensification R&D

Novel technology processes and system design concepts are needed to improve energy efficiency and lower costs for water treatment. New technologies related to water pre-treatment systems (e.g., upstream from the desalination unit operation) and other novel approaches can address associated challenges such as water reuse, water efficiency, and high-value co-products.

Materials and Manufacturing R&D

Materials R&D has the potential to improve energy efficiency and lower costs through improved materials used in specific components and in water treatment systems. Desalination and related water treatment technologies can benefit from materials improvements for a range of products (e.g., membranes, pipes, tanks, and pumps) that dramatically increase their performance, efficiency, longevity, durability, and corrosion resistance.

Data, Modeling, and Analysis

In order to consistently define, track, and achieve pipe-parity in the highest impact areas, strategic, non-biased, and integrated data and analysis is needed. This data, in addition to studies and analysis tools, is necessary to guide the Hub's strategic R&D portfolio. A centralized data system will also fill the void in industry for shared information and provide decision-making tools related to water treatment implementation. Multi-scale models and simulation tools can inform R&D via performance forecasting, design optimization, and operation of desalination technologies and related water-treatment systems, leading into improved energy efficiency and lowered costs.

3. MUNICIPAL WATER USER SECTOR OVERVIEW

This overview of the Municipal Sector provides a high-level synopsis and rationale for this roadmap's focus—expanding the availability and reliability of water supplies with nontraditional water sources.

3.1. Current Municipal Supplies and Demands

There are over 50,000 water systems that serve the Municipal Sector in the United States.‡ They are operated by municipalities, county governments, nonprofit entities, private companies, or special districts (i.e., governmental entities that do not follow traditional political boundaries). These systems provide water for indoor and outdoor use by residential, commercial, institutional, industrial, and irrigation customers and for public services (e.g., firefighting) and other uses.

In 2015, these systems provided almost 148 million m^3 per day (39 billion gallons per day) of drinking water, including leaks and losses in the distribution systems, to 87 percent of the nation's population; the majority of this water is used for residential purposes.[5] **The national average water use in U.S. households in 2015 was 300 liters (83 gallons) per capita per day.**

While the majority of the U.S. population is served by large water systems (serving more than 10,000 persons), the majority of systems are medium or small, which underscores the need for economies of scale in manufacturing that can provide cost-effective advanced treatment technologies at small scales.

The water supplied by these systems is predominantly from:

- 60 Percent **Fresh surface water**
- 38 Percent **Fresh groundwater**

As of 2015, less than one percent of water used by municipal systems was from saline or brackish groundwater sources, and less than 0.02 percent was from saline or brackish surface water sources.§ An estimated 11 million m^3 per day (2,800 million gallons per day [MGD]) of municipal wastewater is also treated for reuse in a few large cities, mostly but not exclusively in arid and semi-arid states. These estimates for reuse are based largely on data reported in 2010[6] and 2012[7] and likely underestimate current volumes. While water reuse only represents about 1 percent of current municipal use nationally, in certain regions (e.g., Southern California and Phoenix) much greater percentages of municipal supply are already met by water reuse; for example, the Orange County Water District (OCWD) in Southern California provides 100 MGD of water from reuse that comprises approximately 35 percent of their service area's groundwater replenishment needs.

‡ A community water system serves a consistent, year-round population of at least 25 people at their primary residences or at least 15 primary residences (e.g., mobile home parks, sub-divisions). This definition excludes public water systems that serve transient or seasonal populations, such as campgrounds or schools.

§ Data from the year 2015 underestimates typical seawater desalination contributions. In 2010, saline surface water use for municipal purposes in the United States was a more expected 89 million liters per day (MLD) (23.5 MGD). For unknown reasons, Tampa Bay Water's 95-MLD desalination plant in Florida reports about 4 MLD in 2015. Operations at the 170-MLD Carlsbad Desalination Plant in California began in mid-December 2015 and were not reported.

3.2. Water Quality Considerations

The Environmental Protection Agency (EPA) sets the legal limits on more than 90 contaminants in drinking water to protect human health; this is codified in the Safe Drinking Water Act (SDWA), a regulation first established in 1974.[8] Most of the water supplied by public water systems is of potable quality, which is fit for human consumption as defined by the SDWA. Water treatment to meet regulated standards for public consumption typically requires complex multi-step processes. The parameters used by EPA to monitor the quality of drinking water include the amount of microorganisms, disinfectants, radionuclides, and organic and inorganic compounds.[9] The SDWA sets minimum standards for safe drinking water; individual states and municipalities often set and enforce their own drinking water standards that are at least as stringent as the national standards.

Some water systems also supply lower-quality water for specific non-potable purposes (e.g., landscape irrigation; cooling towers; certain commercial, industrial, and institutional needs; firefighting).[10] **Non-potable water supply lowers overall treatment costs to meet water demand but requires a separate distribution network** composed of purple pipe, per the U.S. Plumbing Code. Non-potable water typically comes from untreated or minimally treated surface or groundwater or from recycled water.

Non-potable water typically comes from untreated or minimally treated surface or groundwater or from recycled water. Fit-for-purpose approaches have the potential to save water and reduce production costs and energy demands.[11] However, they can add significant cost and complexity to the distribution systems since each "purpose" requires a dedicated piping system connecting the treatment system to its customers.

Some municipal water systems have successfully implemented "fit-for-purpose" water supply when large water customers are in close proximity. The West Basin Municipal Water District provides recycled water at five quality levels for different uses to nearby customers at their 150 MLD (40 MGD) Edward C. Little Water Recycling Facility in El Segundo, California.

These include:

1. Tertiary treated water for general industrial and irrigation use
2. Nitrified water for industrial cooling towers
3. Full advanced treated wastewater for groundwater augmentation
4. RO water for refinery low-pressure boiler feed water
5. Ultra-pure RO water for refinery high-pressure boiler feed water[12]

However, this approach has rarely been replicated at scale because the approach is rarely cost-effective in the majority of settings (i.e., where large water customers are not in close proximity).

In practice, fit-for-purpose water has limited applications in water systems that rely on centralized treatment facilities.[13] Though large treatment plants benefit from treatment economies of scale, there are significant costs associated with constructing and operating separate distribution networks for each purpose. These tradeoffs can potentially be minimized with modular treatment technologies that can be cost-effectively deployed at small scales so treatment occurs close to its final use, minimizing the need for multiple piping networks.[3]

3.3. Water-Energy Nexus in the Municipal Water Sector

Water and energy systems are known to be interdependent; energy production and electricity generation utilize water for cooling, cleaning, and processing supplies. Similarly, public water systems use substantial amounts of energy for supplying water from the source, treating it, distributing it to customers and storage facilities, and treating wastewaters prior to discharge back to the environment.[14]

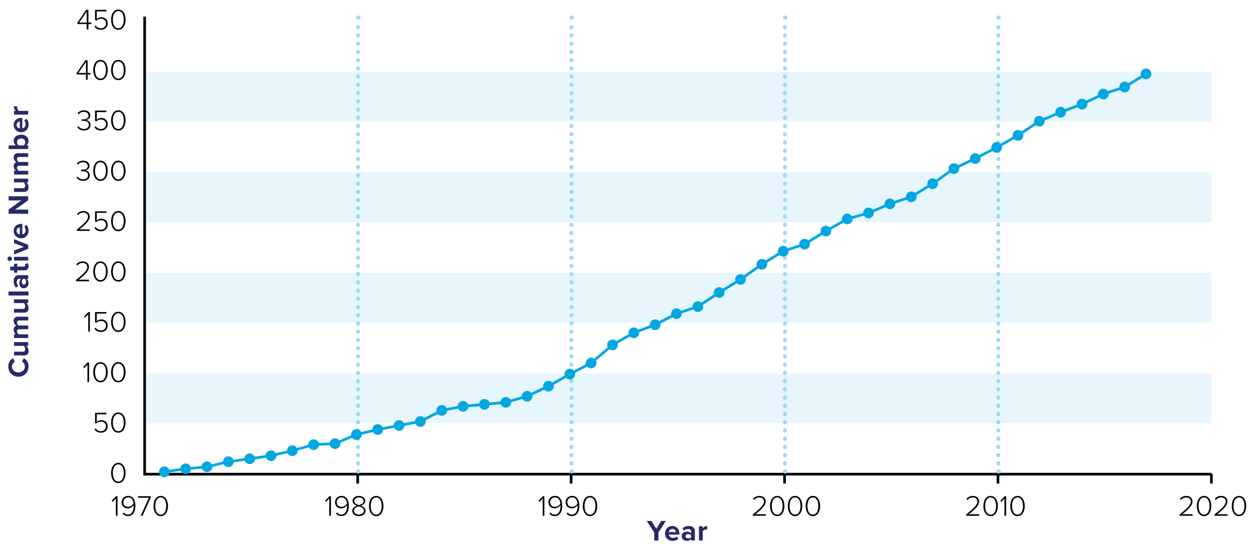
Some examples of energy intensities for the Municipal Water Sector are highlighted below for general context:

- Drinking water and wastewater systems account for approximately 0.5 percent of energy use and 1.5 percent of electricity use in the United States, though these percentages vary significantly.[15,16] In California, water systems consume about five percent of electricity.
- Based on a study of large U.S. cities, the mean energy intensity for supplying potable water is 0.34 kilo-watt hours per cubic meter(kWh/m^{3}) or 1.3 mega-watt hours per million gallons (MWh/MG) with an interquartile range of 0.15–0.5 kWh/m^3; the wastewater energy intensity is 0.42 kWh/m^3 (1.6 MWh/MG) on average (interquartile range: 0.37–0.66 kWh/m^3).[17] In comparison, seawater desalination requires 3.0–3.8 kWh/m^3 in the United States.[18]
- Nationally, municipal water supply and wastewater treatment consume about 70 tera-watt hours per year (TWh/year) of electricity.[19] If recent trends continue, electricity use will increase about one to two percent per year. Widespread adoption of desalination would accelerate electricity use in the water industry.
- An electric energy savings potential of 5–10 percent across the U.S. public water supply can be achieved with advances in pumping and water treatment process control.[20] Assuming the public water supply currently uses about 39 billion kWh per year, the potential electric energy savings associated with advanced supervisory control and data acquisition (SCADA) systems ranges from 2.0 to 3.9 TWh/year. This translates into electricity savings ranging from 5.4 to 10.9 million kWh/day across the United States.[21]
- Water-related energy use by end-users, primarily water heating and cooling, is more than twenty times greater than energy used by the water and wastewater providers themselves in the United States.[19]

To achieve energy efficiency goals set by DOE,[22] innovation in the water sector will need to consider its energy implications.

3.4. Desalination in Municipal Water

In cities, desalination is required for use of seawater and brackish groundwater supplies as well as certain water reuse applications. Seawater comes from coastal surface water, typically the ocean, with a typical TDS of 35,000 mg/L. Brackish groundwater is pumped from underground aquifers and typically has a TDS of 1,000 to 10,000 mg/L. Water reuse in the Municipal Sector uses the effluent of municipal wastewater treatment plants as a water source. The TDS of these sources varies based on the water sources used within the sewershed. Seawater and brackish groundwater desalination are used to produce potable water in cities. Water reuse can produce either potable or



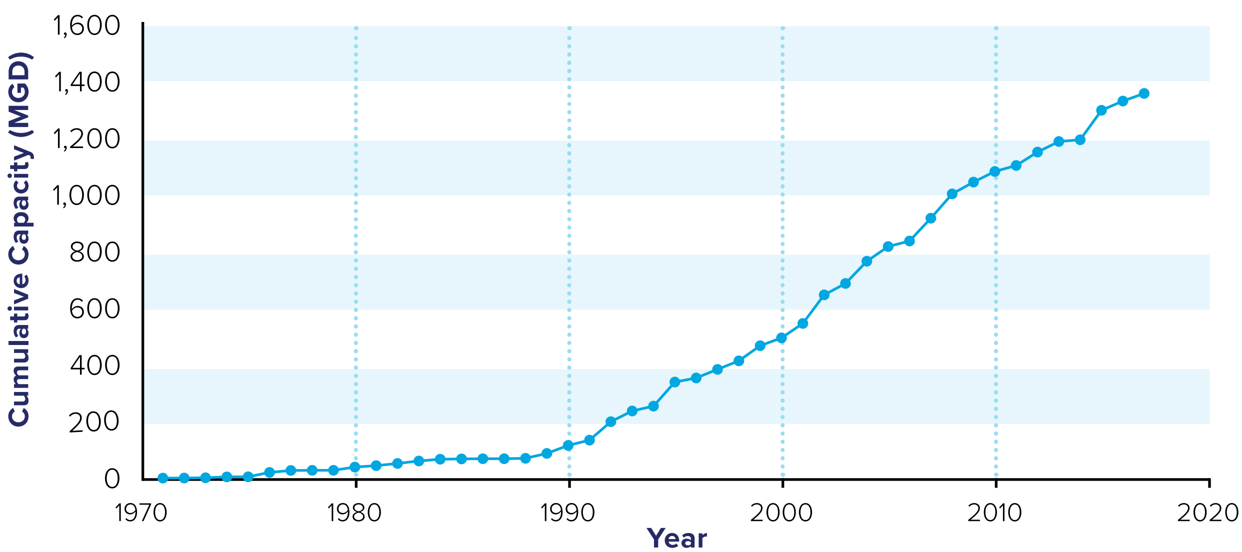


Figure 3. Cumulative numbers and capacity of municipal desalination facilities from 1971 to 2017 in the United States[23]

Source: The Environmental Protection Agency non-potable water.

The last decade has seen considerable growth in desalination and water reuse for potable purposes, as scarcity has driven demand for more reliable supplies (Figure 3).

A survey in 2017 identified 406 municipal desalination facilities that have a cumulative capacity of 5,300 MLD (1,400 MGD). Twenty percent of these facilities were built between 2010 and 2017.[23]

Municipal desalination facilities have been identified in **35 states**, with **more than 68 percent** of such plants located in California, Texas, and Florida.[23] Prior roadmaps outlining research priorities for improving desalination may have contributed to this expanded adoption.[24]

3.4.1. Seawater

As of 2017, there were 13 seawater reverse osmosis (SWRO) plants in the United States, though several more are in the planning stages. Two facilities account for three-quarters of U.S. seawater desalination capacity. The remaining seawater desalination plants all have production capacity smaller than 20 MLD and are distributed between California, Washington, New Jersey, Texas, and the Caribbean Islands. Most treatment facilities include SWRO.

The largest SWRO plant in the United States is the Claude “Bud” Lewis Carlsbad Desalination Plant (Carlsbad) in Carlsbad, California. This 190 MLD (50 MGD) capacity facility has treated water from the Pacific Ocean (35 grams per liter [g/L] TDS) year round since December 2015.

The Tampa Bay desalination facility in Tampa, Florida is the second largest U.S. SWRO plant and started operating in 2007. This facility has a nominal capacity of 95 MLD (25 MGD) and typically operates nine months each year. Because its intake is in Tampa Bay, the feed water TDS is lower than typical seawater and varies seasonally, averaging around 32 g/L. Both facilities are co-located with thermoelectric power plants and use their existing intake and discharge structure. This has been common practice for SWRO facilities globally but raises concerns about how costs would be affected for similar desalination facilities if the adjacent power stations are closed.

Challenges remain for expanding seawater for municipal supply. The design, permitting, construction, and start-up of both Tampa and Carlsbad took years longer than originally expected due to a combination of factors. For Tampa, bankruptcies of construction companies, partnership restructuring, and issues with membrane and filter fouling caused a six-year delay. Similarly, the Carlsbad plant was delayed multiple times due to permitting issues and legal challenges, primarily related to mitigating environmental impacts associated with the plant. Permitting, designing, and building the Carlsbad plant took 14 years. Carlsbad and many other seawater facilities face technical challenges addressing periodic algal blooms, which require either expensive dedicated treatment processes to remove algae or shutting down the plant to avoid damage. The Tampa plant does not operate in the summer when surface supplies are abundant and, therefore, has fewer issues with algae contamination.

Over the past 30 years, significant advancements have been made in ocean desalination technologies, including a two-fold reduction of energy requirements for SWRO membrane desalination.[25] **SWRO technology has replaced the traditional thermal desalination to become the world leading desalination technology.** The world has seen a booming of SWRO plants in the Middle East, Australia, and Mediterranean regions since the late 1990s.[26]

Compared with other alternative sources of water, ocean water is an unlimited and unrestricted source of water supply. Therefore, large scale SWRO plants are a potential solution for providing a drought-proof source of water to cities around the world. In severe water stressed regions such as Israel and the coastal areas of the Southwest United States, ocean desalination is a reliable, climate invariable long-term solution to the escalating water crisis. However, in comparison with seawater desalination plants in Israel, the U.S. plants are more costly, largely due to higher labor costs and longer permitting processes.

3.4.2. Brackish Groundwater

The U.S. Geological Survey (USGS) has identified brackish groundwater supplies in all states, except New Hampshire and Rhode Island.[27] An extensive band of supply runs through the middle of the country, roughly from Montana to Texas. The prevalence and accessibility of brackish groundwater makes it a potential solution to water scarcity concerns nationwide. However, this supply remains underdeveloped due to its complex chemistry and the disposal challenges associated with inland plants.

Brackish groundwater, while defined by its TDS concentration, may contain other constituents that must be removed to protect human or crop health or for efficient downstream treatment. Water quality varies depending on natural conditions and/or human-induced contamination in the aquifer. For example, brackish water in the United States contains arsenic, nitrate, selenium, uranium, radium, heavy metals, chlorinated and fluorinated organic contaminants[28,29] and ions from the dissolution of minerals like calcite and gypsum. The complex chemistries associated with brackish water can complicate treatment. Further, RO treatment produces a concentrated brine stream that must be safely discharged.

Coastal brackish desalination facilities typically discharge their brine to the ocean, similar to seawater desalination facilities. Brine discharge at inland facilities is becoming more challenging as disposal via deep-well injection is increasingly regulated in many states due to concerns over seismicity. For small brackish water desalination plants, the brine is often discharged to a sewer, a receiving water, or evaporation ponds. These options are becoming less practical due to more stringent regulations and high costs when the desalination capacities increase.

One inland brackish groundwater facility that is currently addressing these challenges is the Kay Bailey Hutchinson (KBH) desalination plant in El Paso, Texas. KBH is jointly owned by El Paso Water Utilities (EPWU) and the Fort Bliss U.S. Army installation. This RO-based plant is designed to treat 100 MLD (27.5 MGD), making it the largest inland brackish groundwater treatment site in the United States, though it typically only produces about 30 MLD (8 MGD). Brine is currently pumped to a deep-well injection facility. This disposal option is expensive, so KBH has explored opportunities to valorize constituents from the brine, including gypsum, magnesium hydroxide, and additional potable water.

Figure 4. Reverse osmosis systems used at the KBH Desalination Plant in El Paso, Texas[30]

Source: Texas Water Development Board

3.4.3. Wastewater Reuse

Recycled wastewater has been increasingly used to minimize wastewater discharges to sensitive environments, meet increasing demand, and provide more reliable, local supply in cities.[13,31] In contrast to intentional water reuse, de facto reuse is already widespread with many cities having drinking water intakes downstream of wastewater treatment discharge points in a common watershed.

In this situation, wastewater can compose as much as 16 percent of the water supply, depending on streamflow conditions.[32] Going beyond most unplanned de facto reuse, some coordination at the watershed scale has resulted in strategies to improve water quality in waters receiving treated wastewater. An example of this more intentional de facto reuse is the Tarrant Regional Water District's diversion of water from the Trinity River in North Texas, which receives treated wastewater, to a system of sedimentation basins and wetlands that improve the quality of water before it is available to replenish a reservoir used for drinking water supply.[33]

In the United States, an estimated eight percent of municipal wastewater effluent discharged per day is being recycled through planned reuse.[34] **This alternative water source offers significant untapped supplies in areas facing water shortages.** A recent study estimated that globally only 1.7 percent of municipal wastewater is reused. Reuse has been developed primarily in regions where new freshwater supplies are highly constrained. In Israel about 90 percent of wastewater effluent is currently treated for reuse, primarily in the agricultural sector. Singapore aims to reach 100 percent water reuse for all possible uses. Currently the "NEWater" scheme supplies up to 40 percent of Singapore's water use.[14,35] The longest running direct potable reuse (DPR) facility is in Windhoek, Namibia, where it has been operating since 1968 and now provides over a quarter of the city's total supply.[36]

Early municipal reuse applications were predominantly for centralized non-potable reuse (NPR), typically for irrigation. However, in many cities, the cost of a second "purple pipe" distribution network is prohibitive, and/or there is insufficient demand for NPR supply. As more reliable treatment technologies and control strategies are developed, two alternative approaches to reuse are being explored: decentralized NPR and potable reuse.

Decentralized treatment systems are growing as an approach for collecting, treating, and reusing water onsite at a building or campus or within a small network of clustered buildings (e.g., a neighborhood).[37] Current technologies for treatment at this scale are expensive due to high labor needs for frequent testing to ensure water safety as well as system maintenance. Current commercialized treatment systems also often have not been optimized for energy efficiency. However, with improvements, this approach could be a cost-effective way to provide recycled water near its point of use, reduce pressure on overtaxed wastewater infrastructure, extend constrained water supplies, and provide resilience in urban water systems.

Potable reuse involves the deliberate introduction of advanced treated water as part of the drinking water supply and avoids the issue of having dual distribution systems.

There are four potential configurations for potable reuse:

1. **Groundwater augmentation for aquifer storage and recovery:** Advanced wastewater treatment to potable water quality before introducing it to a drinking water aquifer where additional natural treatment may occur
2. **Surface water augmentation:** Treatment to potable water quality before introducing it to a surface water source (e.g., river, lake, reservoir) where it is stored and receives benefits of dilution and retention time
3. **Raw water augmentation:** Advanced water treatment before introducing it to a raw water supply immediately upstream of a water treatment plant where it will receive additional treatment
4. **Treated water augmentation:** Introduction of recycled water or advanced treated water directly into a potable water distribution system[38] (Figure 5)

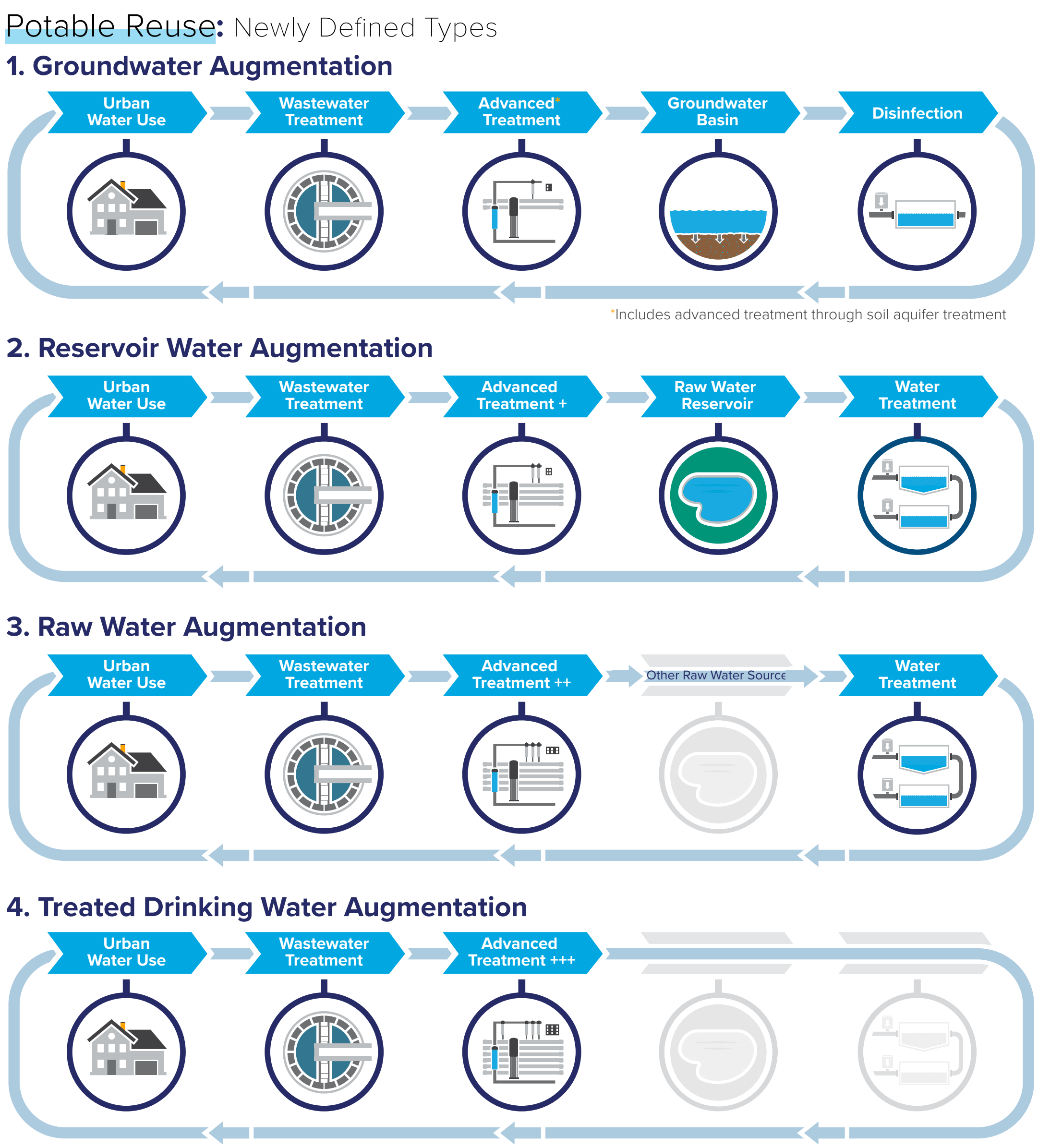


Figure 5. The various types of potable water augmentation

Graphic courtesy of WateReuse California

In other common terminology, groundwater and surface water augmentation are considered indirect potable reuse (IPR), and raw and treated water augmentation are considered DPR. Both IPR and DPR are currently practiced in the United States, and adoption is increasing rapidly.[39] In the United States, there are over 40 IPR facilities and a handful of DPR facilities now operational, under study, in design, or in the approval stages to come online in the near future.[40] These projects span nine states (see Figure 6).[41]

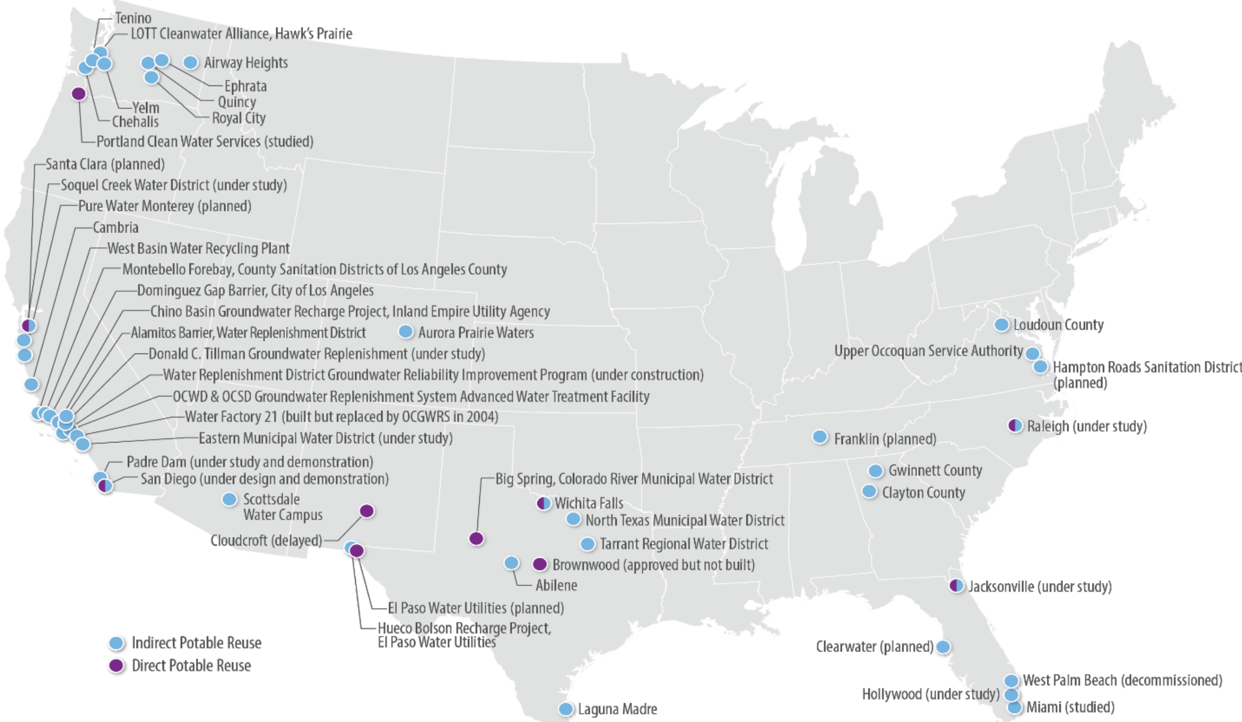


Figure 6. Planned and constructed potable reuse projects in the United States as of 2017[39]

Source: The Environmental Protection Agency

OCWD is an international leader in groundwater augmentation (see box) while its neighbor to the south, San Diego, is developing a surface water augmentation program. Raw water augmentation is being practiced at the Colorado River Municipal Water District Raw Water Production Facility (RWPF) in Big Spring, Texas, which is the only direct potable reuse facility currently operating in the United States. El Paso is designing a treated water augmentation facility after a successful pilot test in 2016. These facilities all rely on treatment trains that include reverse osmosis and an advanced oxidation process. The management of the concentrate stream from the reverse osmosis process is ocean discharge for OCWD, discharge to a naturally high salinity surface water for RWPF, and deep well injection for El Paso.

In contrast to the RO-based treatment systems just discussed, other facilities have opted for treatment trains that do not involve RO to avoid challenges associated with concentrate management. The Aurora Prairie Waters project in Colorado employs river bank filtration, followed by ultraviolet (UV)/advanced oxidation (AOP), biological activated carbon (BAC) and granular activated carbon (GAC) adsorption treatment. The Upper Occoquan Service Authority, which has implemented advanced water treatment for water reuse since 1978, employs a treatment train that includes multimedia filtration and GAC adsorption prior to reservoir water augmentation. Also for reservoir augmentation, the F. Wayne Hill Water Resources Facility in Gwinnett County, Georgia uses ultrafiltration, ozonation, and BAC as part of the treatment process before returning water to Lake Lanier, a key water source for the region.[41]

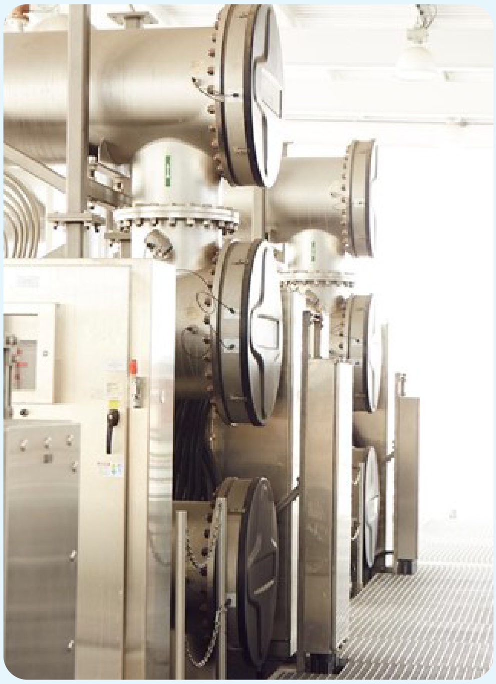
ORANGE COUNTY WATER DISTRICT:

Upon expansion in 2023, this major metropolitan region in the United States will recycle essentially all of the reclaimable wastewater into drinking water.

What is it? OCWD operates the largest potable reuse facility in the world and is a wholesale water agency responsible for sustainable management of the local groundwater basin. OCWD provides groundwater to cities and water districts that serve drinking water to 2.5 million residents in north and central Orange County, between Los Angeles and San Diego. Their state-of-the-art Advanced Water Purification Facility (AWPF) purifies the Orange County Sanitation District's wastewater to recharge OCWD's aquifer for later use as drinking water.

Unique Feature: The highly treated recycled wastewater from OCWD's AWPF is treated through microfiltration (MF) and RO followed by advanced oxidation using high-intensity UV light with hydrogen peroxide (H_2O_2) to disinfect and to destroy any trace organic compounds that may have passed through the prior membrane processes (see figure). Treated water is injected directly into a seawater intrusion barrier near the coast as well as gravity percolated for groundwater recharge.

Capacity: When the Groundwater Replenishment System (GWRS) operates at full capacity (390 MLD / 100 MGD), it can supply a large portion of the water needs of central and north Orange County. The AWPF will be expanded to 130 MGD by 2023.



UV System: A set of UV light and H_2O_2 trains, the third and final step in the GWRS purification process

Image courtesy of OCWD

3.5. Regulatory Standards

The last decade has seen considerable growth in desalination and water reuse for potable purposes as scarcity has driven demand for more drought-tolerant water sources and research on reuse has confirmed the reliability of treatment processes to produce water for human consumption. Currently, there is no uniform desalination and water regulation throughout the nation.[13] Instead, individual states hold the responsibility of developing their own regulatory standards for municipal water use requirements. California has established regulatory standards for desalination and potable reuse. After the challenges of implementing the Carlsbad facility, the state instituted policies in 2016 to establish a consistent approach to permitting and monitoring seawater desalination facilities, including brine disposal. California also has regulations for IPR through groundwater augmentation since 2014 and surface water augmentation since 2018. Standards for DPR through raw water augmentation are expected to be complete in late 2022. An expert panel concluded that it would be feasible to develop uniform water recycling criteria, and it made recommendations regarding aspects of potential regulations.[42] Arizona, Florida, and Texas also have processes for approving potable reuse projects.[39] There are currently no state-level standards for decentralized or on-site NPR. Some cities, including San Francisco, are developing their own ordinances, based in part on guidance from a National Blue-Ribbon Commission.[43]

3.6. Pipe-parity for Municipal Water

For the Municipal Sector, reliably delivering safe water to customers is paramount. Consistently meeting current water quality standards is the primary goal. Many utilities may also consider the ability of new water sources to meet anticipated potential water quality standards. Similarly, the Municipal Sector prefers water sources that can reliably provide the promised volume of water. Many utilities may pay for more expensive water sources that are drought resilient and/or free from competition with other users. RO-based desalination processes consistently provide exceptional water quality across a range of constituents and are drought-resilient.** Because of the low salinity in permeate, RO-treated water is frequently blended with other water supplies allowing use of water with higher salinity without additional treatment. Membrane desalination has provided reliable water sources for many cities experiencing or anticipating scarcity. Water managers in 40 states expect water shortages in some portion of their state in the next several years;[2] many western states are already experiencing water shortages.[41]

Costs are also important because water system budgets may be constrained depending on the capacity to raise water rates, especially given increasing concerns about customer affordability. Energy use may not be explicitly considered, except in localities with greenhouse gas emission reduction goals, or to the extent that; this consideration may be deprioritized if energy consumption contributes to higher costs. Over the past 30 years, SWRO desalination has seen a twofold reduction in the energy requirements for separating water from salts.[44] Costs for seawater desalination have fallen over the same time period. Similarly, costs for other desalination-based processes have seen improvements. In spite of recent improvements, both costs and energy consumption remain higher than conventional surface and groundwater sources across most of the United States. Figure 7 compares the range of costs paid for municipal water supplies in California. Opportunities for additional improvement remain, though there is less room for improvement in seawater desalination, as it already operates near its thermodynamic limit.[3,45]

** Water reuse production can be affected when droughts lead to conservation or rationing in cities but are typically less affected than conventional supplies.

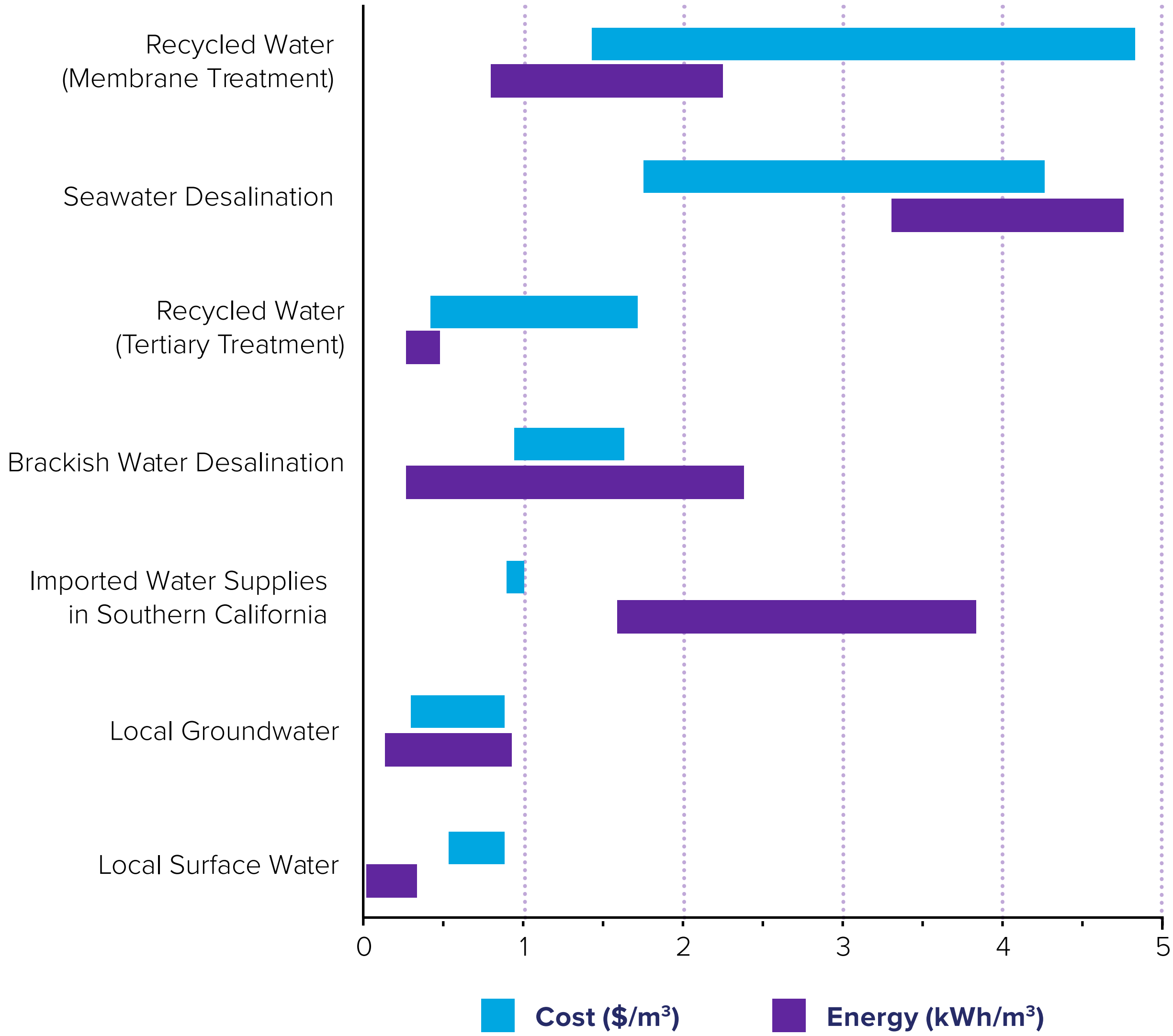


Figure 7. Ranges of cost and energy intensity for California water supplies[46,47,48,49]

Water is a local issue, and the need for desalinated water will vary across the United States. In general, drivers for water supply decisions will be shared by cities with similar climatic, natural resource, and demographic characteristics, which can be grossly defined by the eleven urban megaregions found in the United States (Figure 8).[50] Most urban water suppliers in each region will generally share perspectives on the need for, and value of, alternative water sources. We define urban water suppliers as those serving 3,300 people or more. Urban water suppliers serve about 75 percent of the U.S. population. Smaller water suppliers (serving 10 percent of the U.S. population) and households served by domestic wells (15 percent) may lack the same technical and financial resources as urban water suppliers and, as a result, will evaluate water reuse and desalination differently from the large utilities.

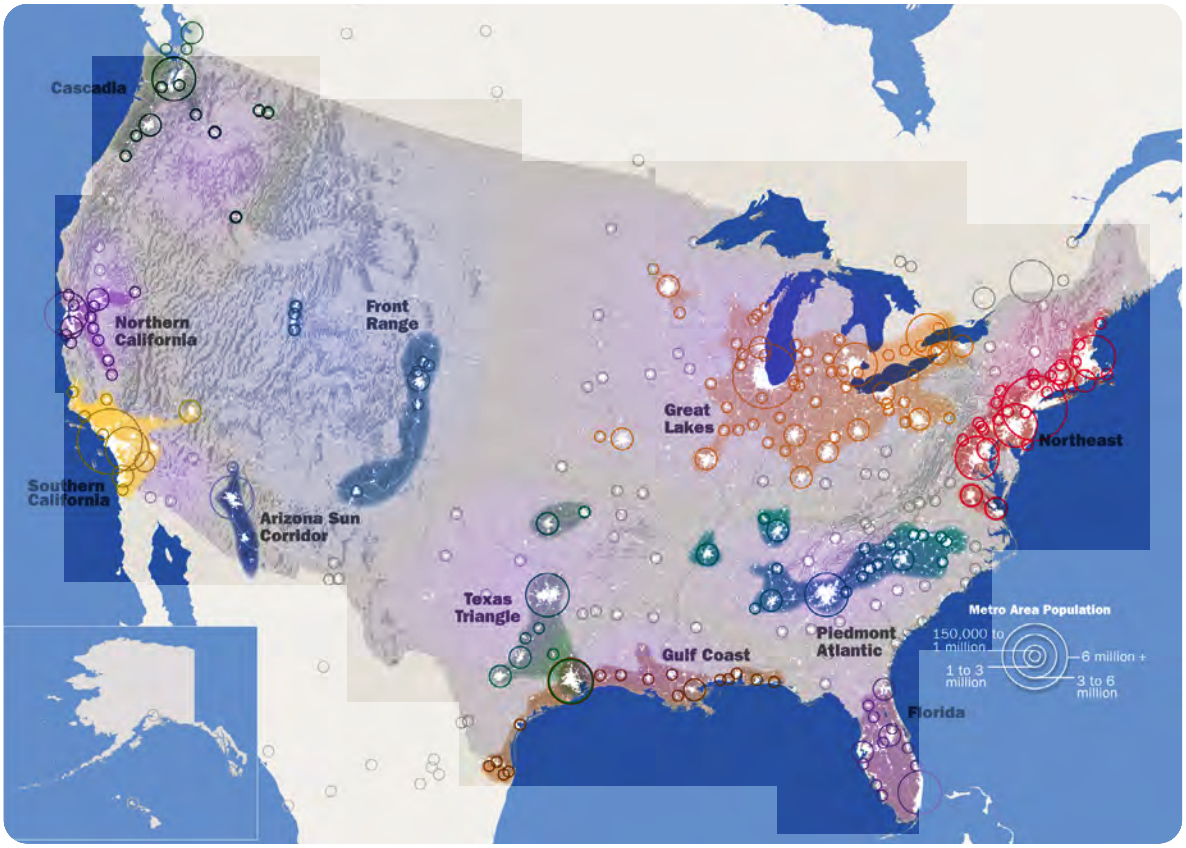


Figure 8. U.S. Megaregions

Source: Regional Plan Association, America 2050: A Prospectus, (2005)

Generally speaking, water reuse and desalination are of most interest and immediate value to cities in the Southern California, Arizona Sun Corridor, Texas Triangle, and Florida regions. These regions experience widespread, routine water stress and have access to alternative supplies. They are likely to be willing to pay more for reliability. Therefore, each of these regions has several seawater, brackish groundwater, and/or potable reuse projects already in operation, indicating that pipe-parity has been achieved in some areas and incremental improvements may significantly expand the use of alternative supplies in these regions. Note from Figure 7 that some California utilities already pay considerably more for desalinated supplies compared to conventional sources that may not be reliable during droughts.

Other regions with moderate or significant localized water stress include the Front Range, Piedmont Atlantic, and Northern California, all of which have a few examples for and growing interest in alternative water supplies. For example, the metropolitan Atlanta, Georgia area in the Piedmont Atlantic region has a rapidly growing economy, but, because it is located high in its watershed, it has limited conventional water supplies. In Atlanta and other large cities in these regions (e.g., Denver and San Francisco), alternative water sources have achieved pipe-parity. However, in cities in these regions with lower water stress, achieving pipe-parity may require substantial technology improvements.

Alternative water supplies are not being pursued in the Cascadia, Great Lakes, Gulf Coast, and Northeast regions, with a few notable exceptions. These exceptions include the potable reuse projects developed by the Upper Occoquan Service Authority and Hampton Roads Sanitation District, both in Virginia, and a large potable reuse facility in Gwinnett County in metropolitan Atlanta, as well as some interest in seawater desalination near the Mexico border. However, because these regions generally have access to sufficient freshwater to meet their demands, it is unlikely that technology improvements will lead to pipe-parity for desalinated supplies in these regions for the foreseeable future.

An analysis by the U.S. Government Accountability Office (GAO) of technologies that address water scarcity reveals results consistent with the regional assessment above.[51] Figure 9 shows adoption rates of nontraditional water sources by EPA region. The greater rates of adoption in the Southern United States are consistent with the regionality approach. An exception is the high adoption rate in the Cascadia region. This likely reflects that the GAO analysis included stormwater capture, a plentiful water source in that region, in its definition of nontraditional water sources. Stormwater and graywater are attracting increasing attention not only in Cascadia but also in more water-stressed regions.[52] Many of the technology improvements that would benefit the integration of other nontraditional water sources into municipal water supplies could also be applied to increased use of captured stormwater and graywater.

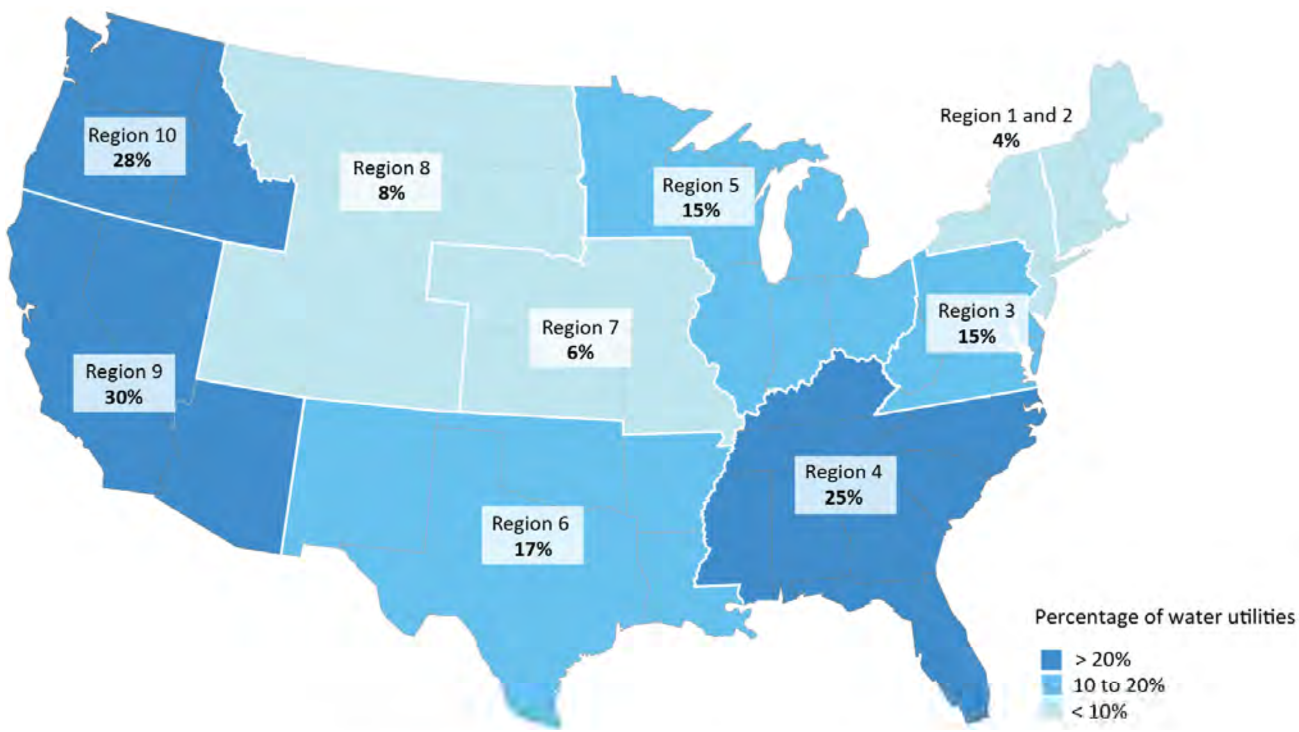


Figure 9. Estimated percentage of utilities treating nontraditional water sources for municipal use, by EPA region

Sources: GAO analysis of EPA data and U.S. Census data; Map Resources (map), | GAO-16-474

3.7. The Municipal Sector's Compounding Water Challenges

In this section, we briefly highlight some significant external pressures on municipal water quantity and quality to provide context around decisions to adopt alternative water supplies: climate change, demographic shifts, contaminants of concern, aging infrastructure, and water rights. This is not intended to be an exhaustive list of challenges or comprehensive assessment of these complex issues. While the objective of the municipal roadmapping effort is to characterize the development of technologies for desalinating and treating nontraditional water sources, the external factors described below influence the trends and forcing functions that will affect technology adoption.

Considering these factors during technology development may eventually improve the technology's application.

Climate Change

Climate change will impact the availability and timing of water resources; sea level rise; flooding; erosion; water quality and, therefore, additional water treatment requirements; wastewater treatment requirements for discharge; and water needs for other economic sectors.[53] Drought and water availability may continue to increase freshwater demand while decreasing supply for some cities.[54] The West will be impacted by more severe droughts and a drier Colorado River Basin, where researchers have found that the annual mean river discharge has been decreasing by 9.3 percent per degree Celsius of warming due to increased evapotranspiration.[55] The quality of water is also impacted by stormwater runoff due to changes in rainfall patterns exacerbated by climate change. Additionally, sea level rise can cause saltwater to intrude into fresh surface and groundwater supplies, forcing water managers to seek other alternative water sources or implement desalination.[15,16] Cities in areas facing climate change-induced increases in precipitation may suffer from sewer overflows and flooding due to earlier snowmelt or extreme weather events.[56] Increasing wastewater system capacity, especially in cities with combined sewer systems, may alleviate these conditions.

Many of these issues will affect demand for alternative water supplies. Climate change is often cited as an important driver of future increases in municipal water withdrawals.[57] A recent Moody's analysis found that "investments in resilience and adaptation will be increasingly important to effectively manage [climate change] risks" and included consideration of the impact of climate change-driven risk on municipal utility bond ratings.[58] Atlanta, Denver, and the Hampton Roads area of Virginia have all invested in IPR to protect existing water supplies, increase water availability, and improve wastewater management to provide more climate resilience.

Factors for consideration, continued.

Demographic Shifts

Demographic shifts, compounded by climate change, may also greatly affect water supply decisions in U.S. cities. Demographic shifts pose challenges for both growing Sun Belt metropolitan areas and for shrinking Rust Belt cities.[59] For example, the Phoenix metro area's population is projected to double by 2040.[60] Reducing per capita water consumption may help the city cope, but increasing water supply also may be required under projected drier climate conditions, as discussed in prior section. Any projected precipitation increases are unlikely to offset this drying trend and may exacerbate water shortage.[61]

In contrast to areas with growing populations, shrinking cities, as we see in the Rust Belt, have challenges as they struggle to cover the costs of stranded water infrastructure assets and manage distribution systems that are both aging and oversized relative to current populations. Such old and oversized infrastructure presents challenges for maintaining water quality throughout the distribution system. **Distributed treatment systems and improved automation and monitoring could provide opportunities to cost-effectively and reliably provide high quality tap water for shrinking cities.**

Containment of Emerging Concern (CECs)

CECs found in many water sources pose potential environmental or public health risks. These contaminants are challenging for water systems because they have adverse health effects at low concentrations and are frequently difficult to remove. Although CECs are not currently regulated at a federal level, several are listed on EPA's 2016 drinking water candidate contaminant list (CCL).[62] EPA uses the CCL to identify priority chemical and microbial contaminants for regulatory decision-making and information collection. Lists are updated every five years as required by the SDWA. The current CCL includes pharmaceuticals, fragrances, surfactants, pesticides, and industrial chemicals like per- and polyfluoroalkyl substances (PFAS), among others. Some of these contaminants can survive wastewater treatment processes and be discharged to surface and groundwater or accumulated in recycled water[39] The risks depend on the source of wastewater being reused. For example, industrial wastewater may contain PFAS and agricultural sources may contain pesticides. Municipal wastewater may contain N-Nitrosodimethylamine (NDMA), pharmaceuticals and personal care products, and pesticides.

Factors for consideration, continued.

Aging Infrastructure

Aging infrastructure will increase the costs of all water supplied, regardless of source. Municipalities supply water to homes and businesses through a network of underground pipes and other infrastructure, much of which is reaching the end of its useful life. It is estimated that there are 240,000 water main breaks across the country each year;[63] the direct cost of these leaks is estimated at $2.6 billion annually.[64] The American Water Works Association (AWWA) estimates that restoring existing underground pipes will cost more than $1 trillion over the next 25 years.[65]

Augmenting or replacing these aging centralized systems with more cost-effective and reliable decentralized treatment systems can potentially protect affected customers from health risks associated with deteriorating infrastructure. A major problem with aging infrastructure in shrinking cities are very high water ages (i.e., the time between when water leaves a treatment plant and when it reaches a customer). Smaller-scale decentralized systems could be implemented in periurban areas to decrease water age and provide higher quality water. While not an option for public water systems in the current regulatory framework, point-of-use treatment systems for household use are modular systems that could provide fit-for-purpose water at the household scale within the context of an overall centralized system facing water quality challenges.

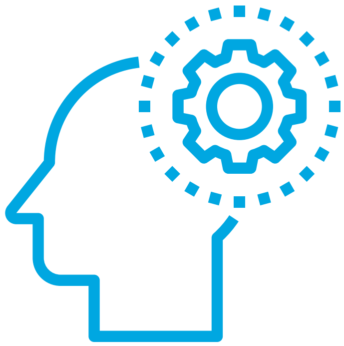
Water Rights

Water rights may limit opportunities to adopt certain alternative water supplies, especially water reuse. A water right entitles the user to use a certain quantity of water from a river, stream, pond, or groundwater aquifer. Water rights are established by states and can vary considerably, even among states with similar hydrologic conditions. Some water rights may assume the continuous presence of return flows (e.g., discharge from wastewater treatment facilities), complicating, if not preventing, reuse in some states such as Colorado and New Mexico.[66] Water reuse planning in inland areas should consider the effect on water rights holders downstream. Further, cities holding lower-priority water rights may have considerable motivation to explore nontraditional water supplies to mitigate the anticipated future supply challenges.

4. TECHNICAL CHALLENGES
And Associated Knowledge Gaps

The Municipal Water Sector is a large processor of water for many different customers; a limited number of municipalities are already using alternative water sources in their supply mix.

In order to expand the availability and reliability of water supplies with nontraditional water sources for the Municipal Sector, existing challenges and knowledge gaps need to be identified so specific technology advances can be developed to address them.



The following sections in this roadmap identify broad industry challenges and gaps (technical and non-technical) that limit integration of nontraditional water sources with existing supplies for this sector. These barriers have been identified through workshops and discussions with subject matter experts, as part of a structured roadmapping process. They are too large and far-reaching for any one organization to devote all the resources needed to develop suitable solutions. ***NAWI intends to invest in promising technologies that are crosscutting across the PRIMA areas and that address some technical limitations discussed below.***

4.1. Technical Challenges

4.1.1. System Durability and Compatibility

Treatment systems for nontraditional water sources may not be durable enough to handle CECs not normally found in traditional water supplies. Advanced water treatment facilities are designed to use a multi-barrier approach (e.g., membranes followed by advanced oxidation processes) to remove contaminants. Nontraditional water sources will introduce new operating challenges to the existing treatment methods for removal of unconventional constituents (e.g., high salinity, CECs). When considering all these issues, there will be a direct impact to the O&M budgets of municipal treatment facilities when considering the use of nontraditional waters.

Aging infrastructure, existing premise plumbing, and discharge to sensitive environment may have compatibility challenges when used with/exposed to nontraditional water supplies. These new supplies will likely have varying water composition chemistries. In order to control corrosion risks, limit production of disinfection byproducts, and limit growth of biofilms, these new supplies will require ongoing chemistry adjustments when exposed to legacy infrastructure and premise plumbing. Additionally, when nontraditional water sources are introduced to existing environmental buffers (e.g., an aquifer) as a part of a water supply and storage strategy, the water quality can be degraded if it mobilizes contaminants from the aquifer (e.g., chromium [Cr (VI)], arsenic [As]) because of a chemical incompatibility of the treated water and the native groundwater. Monitoring and active managing the water quality of those natural systems are needed to ensure the nontraditional water constituents and their varying chemistries do not adversely impact their buffering functionalities.

4.1.2. Monitoring and Detection Limitations

The technologies needed for performance monitoring and safety assurance in municipal treatment and distribution systems are insufficient. The lack of real-time sensors for some of the critical water quality parameters (e.g., real-time monitoring of pathogens in the treatment train, biofouling precursor indicator) limits the timely receipt of data to be able to inform dynamic real-time operations. Furthermore, most of the water data are not directly connected with networked systems to allow for feedback to the system and fully autonomous treatment operations. Remote infrastructure health monitoring systems for evaluating the condition and lifespan of water treatment equipment and distribution pipeline are also lacking.

There is a lack of real-time or near real-time analytical tools capable of measuring and monitoring the broad range of detrimental compounds entering (e.g., biofouling precursors during algal bloom, sudden surge of silica after storm, pulse of PFAS from industrial discharge to wastewater treatment plant) and exiting (e.g., trace organics and other CECs) the water treatment system. Furthermore, detecting low-molecular-weight, non-polar organic compounds that can pass through RO membrane gaps is difficult. Test methods that monitor and detect these compounds in water are time consuming, costly and require well-trained technical personnel.

4.1.3. Inefficient System Designs

Desalination (and inland) treatment processes are typically performed at large, centrally located water treatment plants that consume substantial amounts of energy and have high costs associated with distribution; smaller distributed systems are still not economically viable despite reduced distribution costs. Water recovery is limited to 50 percent for seawater desalination and 80 to 85 percent for brackish water desalination and municipal water reuse. Forty percent of operating costs for drinking water systems can be for energy. These systems treat all water (traditional and nontraditional) to one standard: potability. As detailed earlier, much of this treated water is flushed away and not used for drinking, cooking, or hygiene. Modular, distributed treatment systems that produce different types of water are less efficient or more expensive.

Intermittent supplies of water complicate system operations, impacting the quality and quantity of delivered water. Competition for these alternative water sources from different sectors and industries could constrain steady flows to municipal treatment systems. Additionally, senior water rights, water conservation guidelines, seasonal variations, and groundwater recharge requirements could interrupt consistent supplies to municipalities.

4.1.4. Residuals Management

Municipal water treatment systems have constrained options for managing residuals; the use of nontraditional waters will increase the level of waste management complexities. Water recovery is limited in municipal desalination and treatment systems; this results in significant amounts of waste products such as brines, concentrates, and sludges, among other residuals; these have varying constituents and constituent concentrations. The generation of high TDS concentrate streams from desalination processes poses challenges for inland facilities without access to the ocean as a discharge point.

Management of concentrate streams for inland contexts can add considerable expense and technical complexity to RO-based inland facilities. Selective separation technologies to reclaim high value-added products from treatment waste are not widely implemented because they are currently too complex or not economical for small facilities, these materials are often shipped off premises to undergo further handling at considerable costs. These expenses are attributed to adhering to strict transport and storage safety protocols when handling and moving waste. When treating nontraditional waters, waste management practices will be further complicated since the residuals will have a larger number of constituents (possibly unknown) and under the impact of seasonal water quality variability or other effects.

4.1.5. Workforce and Equipment Development

The use of nontraditional water sources with municipal water systems will require the implementation of complex treatment systems; a skilled workforce may not be available for operating new technologies; for this reason, automation might be necessary. Creating clear operating manuals and standard operating procedures for use with new technologies will enable smooth operations, prevent downtime, and increase efficiency; these trainings will take time to create. Ensuring proper employee training is critical to run advanced treatment systems.

There are limited methods to validate equipment cheaply and effectively while evaluating long-term risks of new technology with new source waters. Equipment validation follows a set of qualification steps to ensure consistent, expected functionality. New test methods and procedures will likely be needed to be able to compare treatment processes at different stages of development and can take time to fully realize. Evaluating long-term public health and ecological risks when using nontraditional waters, in particular managing residual and waste streams, requires expanding standard toxicology, epidemiology, chemical and microbial analysis, and other types of risk assessment.

4.2. Non-Technical Challenges

The list below identifies those non-technical challenges associated with enabling nontraditional water sources to be utilized for the Municipal Sector. These concepts are included here for thoroughness in identifying other kinds of gaps that could limit the use of nontraditional waters but are out of the scope of the NAWI focus. This list is not meant to be exhaustive, but rather a high-level report-out of the main ideas identified during the data collection phase.

4.2.1. Cost

Implementing new technologies often comes with significant adoption costs. The development of nontraditional water sources for municipal use will require sizable investments to develop and qualify the technology fully and manage the additional residuals and concentrates. These can often be passed on to customers, but the situation is often difficult with municipal water systems since they must be able to recover expenditures while keeping their rates affordable to consumers. However, it is anticipated the first few projects cost more as a new technology is spinning up. The adoption costs will drop over time as the industry matures.

4.2.2. Cultural and Societal Challenges

Many utilities have hesitated to embrace the use of alternate water sources due to perceived concerns regarding public health, potential loss of revenue, and diversion of treated wastewater currently meeting ecological needs.[67] Water is critical to any society's wellbeing; the treatment processes, usage, and consumption patterns has taken on cultural, social, and public health dimensions, among others. Municipalities need more complex management practices and more stringent monitoring procedures for integrating nontraditional water sources into their supply mix. Strategies for gaining the public's trust in using these different water sources are critical to address the cultural and societal challenges. Research has identified engagement with a diverse set of stakeholders across issues of pragmatic, moral, and cognitive legitimacy as critical to public acceptance of water reuse projects. Further, ideas of legitimacy can be culturally and regionally specific.[68]

4.3. Regulatory Challenges

Rules, regulations, and laws stemming from local, state, and federal jurisdictions create challenges to potable water reuse in municipal water systems. Local ordinances can restrict the use of reclaimed stormwater for non-potable uses. Additionally, municipalities often need to meet several levels of state and federal regulations before nontraditional water sources can be integrated into the supply mix. The heterogeneity of water rights and water quality regulations creates challenges. In western states, downstream water rights and flow mandates can restrict the reclamation of many kinds of wastewaters. Federal initiatives to replace the traditional, fragmented, siloed approaches to wastewater resources management are evolving[69] and require more time before they are implemented for municipal systems to use.

4.4. Environmental Challenges

Various environmental factors limit access to nontraditional water sources. Climate change, weather patterns, and drought cycles impact access to all kinds of waters. Groundwater quality is deteriorating due to overdraft and lack of recharge and replenishment. Wastewaters are trending to lower and lower qualities due to increasing concentrate salt concentrations, pollution, and contamination. Lowered water quality leads to difficulties in developing effective treatment processes, which reduces the attractiveness of nontraditional source waters for municipal use.

5. RESEARCH PRIORITIES

Areas of Interest for Municipal End-Use Roadmap

To overcome the challenges presented in Section 4, this roadmap identifies the following set of research priorities needed to expand the use of nontraditional sources waters for the Municipal Sector.

All the priorities are grouped under the A-PRIME categories: Autonomous, Precise, Resilient, Intensified, Modular, and Electrified. Advanced desalination and reuse will require a new generation of low-cost, modular processes that are inexpensive to customize, manufacture, operate autonomously, and maintain. This shift to small, connected, "appliance-like" water treatment systems that are mass-manufactured cannot be achieved by simply scaling down existing treatment plant designs or introducing marginal improvements to current treatment processes. Instead, a suite of next-generation desalination technologies that autonomously adapt to variable water chemistry; precisely and efficiently remove trace contaminants of concern; are robust to process upsets; desalinate water and concentrate brines in as few, modular units as possible; are readily manufactured; and do not require a constant resupply of consumable chemical reagents. ***Investing R&D resources in the following priorities will lead to a revolution in desalination and treatment processes for the Municipal Sector.***

Each identified area of interest follows with a short discussion of the current research challenges (a technology or problem that has not been sufficiently answered by existing studies) and continues with specific research needs. Advances in these technologies and capabilities aim to reduce the cost of treating nontraditional source waters to the same range as marginal water sources, thereby achieving pipe-parity. Where possible, quantitative estimates of potential impacts are given. Furthermore, a short discussion on the benefits of new technoeconomic analysis and life cycle analysis research is also provided at the end of this section.

A The **Autonomous** area entails developing robust sensor networks coupled with sophisticated analytics and secure controls systems.

P The **Precise** area focuses on a targeted treatment approach with precise removal or transformation of treatment-limiting constituents and trace contaminants.

R The **Resilient** area looks to enable adaptable treatment processes and strengthen water supply networks.

I The **Intensified** area focuses on innovative technologies and process intensification for brine concentration and crystallization and the management and valorization of residuals.

M The **Modular** area looks to improve materials and manufacturing processes and scalability to expand the range of cost-competitive treatment components and eliminate intensive pre/post-treatment.

E The **Electrified** area aims to replace chemically intensive processes with electrified processes that are more amenable to variable or fluctuating operating conditions.

5.1 Autonomous

Sensors and Adaptive Process Controls for Efficient, Resilient, and Secure Systems

A1. Develop inline or near real-time sensors for pathogens and CEC removal monitoring for municipal waterwaste reuse.

Challenges

Adoption of alternative sources of water supply to meet municipal water demands is challenged by the various impurities and constituents in nontraditional sources of water. Although wastewater reuse has been applied and is broadly accepted in water-stressed regions for non-potable purposes, the use of treated wastewater for drinking water supply has been met with various concerns. Municipal wastewater contains high concentrations of pathogens (i.e., bacteria, viruses, and protozoa), antibiotics, pharmaceuticals, and other CECs. Despite the high efficiency for removal of these impurities by reverse osmosis, some microbial pathogens, such as human viruses, and small molecular weight organics, such as 1,4-dioxin, may break though the membrane barrier. Real-time or near real-time sensors for pathogens, especially viruses, and trace organic compound (or a surrogate of small organic molecules) removal are needed to ensure the proper function of the engineered barriers and designed removal efficiency.

Real-time fault detection would also instill confidence in end users for accepting the recycled wastewater as a drinking water supply. Portable, rapid, and easy-to-use sensors could also promote localized water reuse at the building scale by offering rapid test results with minimal technical training. Moreover, real-time sensors for in-situ biofouling or scaling propensity detection can trigger adaptive treatment options to alleviate severe fouling before the shutdown of a desalination or water reclamation facility.

Impacts

Reliable, real-time pathogen and chemical contaminant sensing would enable broader adoption of municipal wastewater sources for centralized systems as well as foster expansion of decentralized systems, especially for potable water reuse. Municipal system levelized costs of water (LCOWs) appear to be highly sensitive to capacity factor/downtime, so early—or even predictive—detection of disruptions could improve LCOWs for seawater, brackish water desalination and municipal wastewater reuse. This has national relevance for all municipal reuses.

A1.

RESEARCH NEEDS:

- **Develop** inline or near real-time pathogen sensors (especially viral sensor) based on advancements such as microfluidic or 3D printing technologies that have significantly improved pathogen diagnostics in clinical settings. Advances are needed to detect pathogens or pathogen indicators quantitatively in complex environmental matrices and at human health relevant concentrations (TRL 3–4; 2–4 years).
- **Advance** electrochemical sensing and bio-sensing through the understanding of specific chemical and physical interactions and kinetics between sensing substrates and water constituents to achieve the sensitivity, selectivity, and accuracy required for water reclamation (TRL 2–4; 4–5 years).
- **Investigate** and fabricate new materials that have novel surface properties (i.e., surface-enhanced Raman scattering) for molecular recognition to achieve label-free sensing of trace organic compounds of concern (TRL 2–4; 3–5 years).

A2. Develop new approaches for remotely verifying the performance of building-scale and point-of-use treatment systems.

Challenges

Point-of-use treatment units for small water systems could break through regulatory and ownership barriers to implementation as components of a public water system if they are modular with reliable tools that enable automated responses to system changes and remote monitoring of performance. Technologies are already available for modular on-site use (e.g., UV disinfection, selective adsorbents, low pressure nanofiltration [NF]/RO), but barriers remain to verifying performance. Technologies for remote verification of performance can also benefit small-scale centralized systems as well as enable greater implementation of fit-for-purpose water at the building scale, with on-site reuse systems being integrated with point-of-use systems that upgrade the water to the necessary quality, including for potable consumption.

Impacts

Remote operation reduces labor costs and could support growth of third-party service providers; broader adoption of decentralized systems could lead to the creation of a new business sector. Centralized systems with remote facilities would benefit as well. Remote operation and data acquisition are especially important for distributed and building-scale water reuse systems, including on-site reuse of graywater and collection and treatment of rainwater. Distributed and building-scale water treatment systems can reduce the energy and infrastructure needed for water transport for both urban communities as well as suburban areas. In addition, remote operation can facilitate the development of small-scale seawater desalination systems for isolated communities (e.g., island communities) to provide a viable and reliable source of water supply.

A2. RESEARCH NEEDS:

- **Develop** sensors and data transmission systems for monitoring regulated contaminants (e.g., arsenic, hexavalent chromium) in the water produced by autonomous point-of-use treatment systems (TRL 4; 2–5 years).
- **Advance** data science for verifying the performance of a network of distributed point-of-use treatment systems for compliance with drinking water regulations (TRL 4; 2–5 years).

A3. Create sensors or sensor groups that can report the propensity of fouling and inorganic scaling.

Challenges

Municipal drinking water production by seawater or brackish water desalination offers a drought-proof source of water supply. However, RO membrane fouling (including biofouling) and scaling exacerbate the already expensive water production cost. Membrane fouling is described as the Achilles' heel of membrane technology. Membrane fouling reduces water productivity, degrades water quality, and increases energy and chemical cost for cleaning. Frequent membrane cleaning also significantly shortens membrane lifespan. Detection of fouling propensity can offer an early warning for adoption of strategies for membrane fouling prevention. Yet, practical sensors for fouling detection have not been commercially adopted by the desalination industry.

Further research is needed to develop the practical sensor technologies and to understand the industrial implementation needs. Sensors that can report bulk water quality characteristics (e.g., multiple sparingly soluble ions and dissolved silicon dioxide[SiO_2]) will reduce the cost of equipment and personnel to manage multiple sensors. Inline sensors for algal blooms, transparent extracellular polymer substances produced after an algal bloom, and bacterial biomass and bioactivity would be valuable for predicting the propensity of biofouling. Rapid detection of these challenging water constituents could allow adjustment of treatment or pre-treatment technologies to prevent system failures or poor finished water quality. Real-time monitoring ensures the proper function and lifespan of water treatment plant equipment and distribution systems.

Impacts

Sensors and sensor arrays are applicable to all source water treatment systems for municipal water production. For brackish waters, inorganic scaling is the most critical issue for brackish water membrane desalination. Sensors that can predict the early scaling potential will allow the action of cleaning in place (CIP). All seawater desalination plants in the United States can benefit from sensor technologies that provide greater insights into fouling. Sensors that can detect specific algal species during blooms and bioavailable nutrients and assimilable organic carbon that support the proliferation of biofilm-forming bacteria could trigger changes in pretreatment to prevent severe fouling and subsequent downtime in plant operation. Inline and membrane-based sensors can trigger automatic cleaning rather than delaying the cleaning action until there is an observed reduction of water permeability. Biofouling is one of the most important issues in seawater desalination plant operations; it could cause an up to 50 percent energy penalty to pump the water through the membrane during the time of algal blooms compared to normal operations. Fouling sensors can also reduce plant downtime for cleaning and replacement.

A3.

RESEARCH NEEDS:

- **Develop** sensors that can detect multiple sparingly scale-forming solutes (e.g., calcium, magnesium, dissolved silica) simultaneously to predict scaling propensity (TRL 3; 2–3 years).
- **Create** inline sensors for monitoring assimilable organic carbon, organic carbon to nitrogen ratio, biomass, and bioactivity to predict biofouling propensity (TRL 2; 3–5 years).
- **Provide** manufacturing methods for disposable sensors that are inexpensive and easy to replace to remove the human cost of sensor calibration and maintenance (TRL 3; 2–3 years).

A4. Develop digital twins of water treatment plants and artificial intelligence to drive the autonomous operation of treatment plants.

Challenges

Current water treatment operation requires well-trained engineers and experienced operators to perform routine checkups on the plant. They review data collected by meters, gauges, and sensors as well as lab results from grab samples to determine the plant operational efficiency and make adjustments when necessary. The current operation is not only demanding on human resources, but it also has the potential to introduce errors due to the delay of data and the involvement of human decision on the operation. Significant advancements have been made in artificial intelligence to learn patterns and develop algorithms for controls and outcome predictions. A digital revolution has already begun in the water industry, but it requires new system optimization at a fundamental level before its adoption and the realization of pipe-parity savings. The effort to drive toward automated processes for municipal treatment systems is motivated by the Water Technoeconomic Assessment Pipe-Parity Platform (Water-TAP3) observation that O&M expenses account for 14 percent of the cost of desalination at the Carlsbad plant.

Creation of digital twins of water treatment process and treatment trains requires solid operational data collected from sensors. The outcomes from modeling and simulations are only useful when adequate data are acquired and used as input parameters with a high degree of certainty. Research at TRL 2–4 on integration of data with artificial intelligence software and digital control is needed to achieve autonomous water treatment.

Impacts

Digitalization of water treatment plants is applicable to all water treatment plants for municipal water production in the United States, regardless the source of water. The digitalization can be implemented through retrofitting or during the development of treatment plants. Seawater desalination is a long-term reliable source of water supply to the water-stressed coastal regions in the United States. It is anticipated that up to 15 percent of future water could come from seawater, and digitalization should be implemented in all new developments of ocean desalination plants.

A4.

RESEARCH NEEDS:

- **Create** digital twins of water treatment plant operation that incorporate influent water quality, treatment processes, and effluent water quality as input parameters to optimize process operation, cost, and energy (TRL 4; 1–2 years).
- **Use** artificial intelligence that enables learning of water quality inputs and system operation to predict output water quality (TRL 3; 1–2 years).
- **Integrate** set critical control point (CCP) of water quality parameters (e.g., turbidity, bioavailable organic carbon) with dynamic control models to autonomously determine treatment process actions (e.g., coagulant dosing or backwash frequency) (TRL 3; 1–2 years).

5.2. Precise

Targeted Removal of Trace Solutes for Enhanced Water Recovery, Resource Valorization, and Regulatory Compliance

P1. **Develop technology and engineered materials for selective adsorption, destruction, or removal of target constituents and in situ regeneration of selective adsorption sites on engineered material surfaces.**

Challenges

Current water treatment technologies are effective for removal of most particles, bulk organics, and even the majority of solutes in water. However, subsets of water constituents or high concentrations of specific pollutants in alternative sources of water supply present significant challenges to the current water treatment industry. The high concentration of sparingly soluble minerals and metals in seawater and brackish water can cause severe scaling in desalination facilities. Boron cannot be efficiently removed by seawater desalination RO membranes when it is present as neutral molecules in seawater, although its negative impacts are primarily limited to irrigation of citrus. Many neutral low-molecular-weight organic compounds (e.g., 1,4-dioxane) are not removed well by RO and are resistant to degradation by AOPs. Wastewater that is rich in organic carbon and microorganisms can lead to the formation of biofilms on pipes and membrane surfaces for water treatment. Biofouling is also commonly observed in seawater desalination plants during algal blooms. These troubling constituents reduce water treatment efficiency and drive up the energy cost for water treatment.

Organic fouling and subsequent biofouling are detrimental to membrane systems. For precision separations selective binding of target contaminants within complex matrices is challenging. For surface-active materials, there are knowledge gaps regarding performance changes over time due to fouling or catalyst poisoning and maintenance or regeneration of surface functionality. Precision separation of hard-to-treat water constituents either during pre-treatment, treatment, or post-treatment could significantly improve water treatment efficiency, which could lower the energy demand and cost.

Impacts

Selective removal of target constituents has important applications in municipal desalination. For example, all seawater desalination plants can benefit from selective removal of boron using new technology or engineered materials. Selective removal of boron may result in a 20–30 percent reduction in capital investment for installation of a second-pass RO membrane.

Targeted bioavailable organic nutrient removal technologies in ocean desalination pre-treatments may result in up to 50 percent energy savings during periods of algal blooms. Many water utilities have selected RO to remove arsenic, fluoride, nitrate, selenium, radionuclides and CECs in brackish water and reclaimed water. Developing technology and engineered materials for selective adsorption, destruction, or removal of target constituents has national impact to provide alternative low-cost technologies for treatment of low-salinity nontraditional water without the use of desalination processes.

P1.

RESEARCH NEEDS:

- **Combine** modeling and materials science approaches to develop new materials (e.g., nano-composite materials, metal-organic frameworks, covalent-organic frameworks, biosorbent proteins, ion exchange resins) with improved physical-chemical based adsorption to separate target ions or organic molecules from complex water matrices (TRL 2–4; 2–4 years).
- **Combine** new materials with electrically-driven processes (e.g., electrosorption, electrocatalysis, and electrocoagulation) to improve the selectivity and control of separations (TRL 2–4; 2–4 years).
- **Develop** new pre-treatment methods (e.g., chemical, physical, biological, electrical, electrocatalytic, or hybrid) that can effectively remove sparingly soluble inorganic contaminants, algae, and bioavailable organic carbon (TRL 2–4; 2–4 years).
- **Develop** new post-treatment methods (advanced oxidation, reduction, sequential chemical precipitation, photocatalytic reaction) to remove toxic compounds and recover valuable chemicals from desalination discharge brine (TRL 2–4; 2–4 years).
- **Design** and fabricate engineered materials with capacity for in situ regeneration of adsorption sites on surfaces (TRL 2–4; 2–4 years).

P2. Enhance biological treatment for removal of nutrients, organic compounds (CECs, organic and biofouling constituents), and inorganic contaminants (TRL 2–4, 2–5 years).

Challenges

Biological treatment has been an important process to remove bulk organic carbon from wastewater. However, it is less efficient for removal of nitrogenous compounds and trace organic contaminants. Biological methods are known to remove some inorganic contaminants (e.g., selenium) but have not been thoroughly investigated, and they have rarely been implemented in municipal drinking water treatment. While membrane bioreactors provide modular treatment that addresses multiple treatment objectives that makes them suitable for on-site reuse, they can be expensive to operate.

Biological treatment is currently absent in seawater and brackish water desalination industries. Research at TRL 2–4 on enhancing biological treatment and developing salt-tolerant biofilters has the potential to achieve lower energy cost for municipal water production from wastewater, seawater, and brackish water.

Impacts

Improvements in the capabilities of biological treatment processes and their deployment can have national-scale impacts for the Municipal End-Use Sector. While biological treatment is inherently part of the treatment processes upstream of reuse facilities that use treated municipal wastewater as their influent, biological treatment has potential benefits for the use of brackish water and seawater. Biofiltration or membrane bioreactors have the potential to be used as pre-treatment for the desalination process to control organic carbon level to prevent biofouling of desalination membranes. Biological approaches to mitigating fouling (e.g., phages as natural biocides) could decrease the use of chemical biocides.

Enhancing biological treatment and developing salt-tolerant biofilters has the potential to achieve lower energy cost for municipal water production from wastewater, seawater, and brackish water. Understanding of the microbiome of treatment and distribution systems can be used to improve the biological stability of finished water. For low-salinity nontraditional source waters, such as municipal wastewaters in much of the eastern United States, biological treatment is already combined with ozone and GAC to provide high-quality potable water without use of RO.

P2.

RESEARCH NEEDS:

- **Investigate** the microbial ecology and physiology of bio-mineralization, bio-transformation, and bio-adsorption in water treatment relevant settings to develop new biological processes for selective removal of hard-to-remove contaminants (TRL 2–3; 3–5 years).
- **Develop** innovative biological reactors through selective cultivation of microorganisms with specific degradation function and engineering of the microbiome to accelerate the removal of nutrients, organic compounds (e.g., CECs) and other hard-to-remove contaminants for drinking water treatment and pre-treatment (TRL 2–3; 3–5 years).
- **Investigate** biological pre-treatment methods for seawater desalination to remove bioavailable carbon and nutrients for reduction of biofouling (TRL 3–4; 3–4 years).
- **Combine** biological function with engineered adsorbent materials to perform in situ degradation of immobilized contaminants (TRL 2–4; 3–5 years).

5.3. Resilient

Reliable Treatment and Distribution Systems that Adapt to Variable Water Quality and are Robust to Corrosive Conditions

R1.

Improve and evaluate materials and surface capabilities for resisting fouling, scaling, and corrosion.

Challenges

With greater use of nontraditional source waters, especially municipal wastewater and seawater, influent composition to a facility can vary diurnally, episodically (e.g., when it rains), seasonally (e.g., during algal blooms) and over years (e.g., through changing dischargers or conservation efforts). Early-stage research and development is needed in materials, process engineering, and fundamental science that can allow water systems to become more resilient to variations in water supply, operations, and finished water blends.

Current corrosion-resistant materials are often expensive, and there are knowledge gaps regarding the ability of alternative corrosion-resistant materials to meet the treatment demands of components currently made from stainless steel. Fouling-resistant membranes, spacers, and high-permeability membranes have shown promise at bench scale, but they are rarely adopted in the water treatment industry due to the high manufacturing cost. RO membranes are sensitive to oxidation; residual chlorine and other oxidative agents in feed water can damage the polyamide thin film on membrane surfaces. Chemical cleaning is effective for resolving fouling and scaling of membranes and other materials, but membrane degradation may occur after cleaning. Many novel materials for treatment processes are incompatible with the cleaning solutions currently used.

Impacts

With its emphasis on materials and surface capabilities independent of application area, research advances in this area will have a broad reach. The advances to be made here are fundamental to any treatment processes for which fouling, scaling, and corrosion are relevant, which essentially involves all water treatment in the country. Specific advances in corrosion-resistant materials are relevant to all treatment facilities, but they are particularly relevant to those using brackish water and seawater. RO membranes that can be cleaned by more aggressive solutions without degradation of the membranes are applicable to all applications that use RO.

R1.

RESEARCH NEEDS:

- **Identify** components of treatment and distribution systems where new corrosion-resistant materials (e.g., plastics, composites, novel metals) would be cost-effective, and evaluate their performance at relevant chemical, electrochemical, and physical conditions (TRL 2–4; 2–5 years).
- **Develop** fouling- and oxidant-resistant membranes (e.g., ceramic) that are cost-effective and evaluate their performance at water treatment relevant conditions (TRL 2–4; 2–5 years).
- **Develop** materials that are more compatible with chemical cleaning that resolves fouling and scaling (TRL 2–4; 2–5 years).

R2. Develop materials that have longer lifetimes and that can be designed for easier reuse, remanufacture, or recycle.

Challenges

Replacement of treatment components represents significant operating and maintenance costs that could be lowered by increasing the lifetimes of treatment components. The deployment of point-of-use treatment systems, which can take advantage of localized resources and reduce the water conveyance cost, is limited by the need to replace consumable components. Many components are replaced based on schedules of fixed time intervals, and approaches that enable real-time and inherent material indicators of performance that would enable performance-based replacement cycles are not widely available. Green engineering principles of designing for reuse and recycle have not been broadly applied to water treatment technologies.

Impacts

The focus of this area of interest on materials with longer lifetimes and that can be designed for easier reuse, remanufacture, or recycle, is relevant to all water treatment plants with components that require periodic replacement (e.g., membranes, sorbents, catalysts). Consequently, the reach of this area is broad and national in scale. It is particularly relevant to those processes that have replacement times on the order of just a few years. Longer-lasting materials and materials that have inherent indicator or reporter features that provide information on performance can be especially beneficial to small public water systems as well as point-of-use systems.

R2.

RESEARCH NEEDS:

- **Develop** materials (e.g., plastic, composite, ceramic) with increased lifetimes that will enable cost reductions at large facilities and improve the viability of point-of-use treatment systems (TRL 2–4; 2–5 years).
- **Create** new materials that have inherent indicator or reporter features that enable replacement cycles based on material performance and allow fuller utilization of their capacities (TRL 2–4; 2–5 years).
- **Advance** the application of green design principles in the development of materials with greater ease of recycle, reuse, and remanufacture that can enable reductions in life cycle costs, energy use, and environmental impacts (TRL 3–4; 2–4 years).

R3. Improve mechanistic understanding of processes needed to maintain desirable water quality when advanced treated water is introduced to existing distribution and storage infrastructure.

Challenges

Early-stage research and development are needed to improve mechanistic understanding of processes that can degrade finished water quality during storage and transport. Analysis of the OCWD Groundwater Replenishment System in the Water-TAP3 tool reveals that storage and transport functions account for around 11 percent of the cost for water. Water quality can become degraded during distribution and storage as a result of metal corrosion, biofilm formation and sloughing, growth of opportunistic pathogens, and generation of disinfection byproducts. These processes are influenced by the water pH, major anion and cation composition, disinfectant concentration and type, microbiome, and the concentrations and properties of dissolved organic carbon. Remineralization of desalinated water from RO can provide the desired alkalinity and pH, but there may also be a need to reintroduce magnesium, a constituent that it is currently difficult to remineralize.[70] When integrating advanced treated water with an environmental buffer (e.g., aquifer or reservoir), information on the fundamental processes at mineral-water interfaces that can mobilize naturally occurring contaminants like arsenic and chromium(VI) is needed to develop strategies to minimize their mobilization and models to predict their transport.

Impacts

This area of interest has national reach because it encompasses all water treatment systems that are integrated with existing distribution and storage infrastructure. It is also of broad relevance because of its emphasis on improved mechanistic understanding not tied to any one type of source water. Research in this area is needed so that new investments in water treatment technologies are not undermined by downstream problems when that water encounters infrastructure.

R3.

RESEARCH NEEDS:

- **Develop** methods for the remineralization of desalinated water with magnesium in addition to calcium (TRL 2–4; 2–5 years).
- **Quantify** the rates and extents of processes at mineral-water interfaces and improve our ability to predict their impacts on water quality for conditions relevant to the introduction of advanced treated water to an environmental buffer (TRL 2–4; 2–5 years).
- **Advance** knowledge of fundamental processes of metal corrosion, biological growth, biofilm detachment, and disinfection byproduct generation at conditions relevant to the blending or replacement of conventional water sources with advanced treated waters (TRL 2–3; 2–5 years).

R4. Advance understanding of fundamental mechanisms of fouling, scaling and corrosion.

Challenges

New solutions to many of the complications that limit the resilience of current water treatment and supply systems (e.g., fouling, scaling, and corrosion) will benefit from advances in understanding of the underlying physical, chemical, and biological aspects of these phenomena. Biofilm formation and heterogeneous nucleation and crystal growth remain frontier research areas. Research that advances knowledge of fundamental nucleation and crystal growth and the microbial ecology of biofilm formation at conditions relevant to water treatment and supply can provide a bridge between basic interfacial science and early-stage water treatment research and development. Revolutions in molecular microbiology, the microbiome of the built environment, and an array of chemical, physical, and biological tools have not been fully brought to bear on understanding processes in water treatment and supply.

Impacts

This area of interest is so fundamental in nature that it is inherently of broad national reach. With improved mechanistic understanding of fouling, scaling, and corrosion, any water treatment system that is affected by these processes can benefit from the design of technologies built on the underlying new scientific understanding. The greatest benefits may be in areas impacted by biofouling, which especially includes seawater and municipal reuse systems, where revolutions in molecular microbiology and the microbiome of the built environment can lead to potential improvements.

R4. RESEARCH NEEDS:

- **Apply** emerging tools that can identify factors that govern biofilm formation and yield insights into strategies for inhibiting biofouling by means other than application of chemical oxidants or removal of bulk organic carbon (TRL 2–3; 2–5 years).
- **Advance** understanding of nucleation and crystal growth at conditions relevant to water treatment and supply (TRL 2–3; 2–4 years).

5.4. Intensified

Systems and Process Optimization to Maximize Brine Reuse, Improve Brine Concentration and Crystallization, and Manage Residuals

I1. Develop innovative technologies to reduce the volume of concentrate for disposal, achieve near ZLD, and couple brine management with resource recovery and chemical synthesis.

Challenges

Brine management is a significant challenge for implementing and expanding brackish water desalination, seawater desalination, and water reuse for municipal applications, especially in inland areas where concentrate disposal options are limited. At the Kay Bailey Hutchinson Desalination Plant, concentrate management along with waste product storage and disposal processes account for more than 12 percent of the cost of water and 4 percent of the electricity usage.

Better brine management would undoubtedly lead to more implementation of brackish water desalination and municipal water reuse. Innovative technologies for brine treatment to reduce brine volume for disposal and crystallization to achieve ZLD would reduce the costs and energy intensity of small-scale and inland desalination facilities by eliminating the need for brine conveyance, increasing energy efficiency, reducing dependence on finite injection well capacity, and enhancing water recovery. In addition to brine treatment, there are early-stage research needs to manage other residuals produced from municipal water treatment.

With advances in precision separation, extracting valuable minerals and chemicals from waste streams can further increase product water yields. Resource recovery also reduces disposal cost, pairs brine quality with industry needs, and creates revenue from commercial product sales.

Impacts

In the United States, 46 percent of municipal desalination plants discharge brine concentrate to surface water (including ocean water), 24 percent discharge to sewer or wastewater treatment plants, and 17 percent dispose brine through deep well injection. **As plants grow larger, the impacts of concentrate disposal on surface water or wastewater treatment plants (WWTPs) will become more significant and push more facilities toward alternative concentrate disposal options** such as treatment to remove the contaminants before disposal, volume reduction or concentrate minimization, ZLD, and brine valorization. This trend is likely to continue as regulations on concentrate disposal become more stringent, therefore potentially affecting nearly all desalination facilities in the United States. Municipal ZLD has potential for application in semi-arid or arid inland water reuse facilities looking for ways to manage their concentrate streams.

I1.

RESEARCH NEEDS:

- **Develop** cost-effective and energy-efficient alternatives (e.g., ultrahigh-pressure RO, multi-effect membrane distillation, electrodialysis brine concentrators, humidification/dehumidification, and forward osmosis) to traditional, thermally driven brine management technologies (TRL 2–4; 2–4 years).
- **Develop** destructive methods to degrade contaminants (e.g., trace organic compounds and PFAS) in brine and residual (TRL 2–4; 1–5 years).
- **Design** sustainable ZLD technologies, including enhanced evaporation, small-scale concentrators and crystallizers, and brine solidification and encapsulation to avoid leaching during landfill (TRL 2–4; 1–4 years).
- **Develop** innovative processes that leverage multiple driving forces and multiple functions to improve system efficiency of brine treatment (e.g., electrically heated membrane distillation, electroactive membranes, and electrocatalytic membranes) (TRL 2–4; 1–4 years).
- **Develop** cost-effective technologies to extract metals and minerals from brine and residual, and generate process chemicals onsite (e.g., bleach, H_2O_2, acids, and bases) (TRL 2–4; 1–4 years).

12. Develop advanced geochemical modeling and in operando monitoring tools to characterize and understand precipitation, nucleation, crystallization, solute activity, and heat transfer in high-salinity waters.

Challenges

Brines contain high levels of salts that can cause scaling and corrosion in treatment units, equipment, and pipelines. Using in operando monitoring tools and developing advanced geochemical or biogeochemical models to predict chemical change, speciation, and precipitation would significantly reduce the cost of brine management. However, modeling brine streams is difficult due to the complex constituents in brine and the lack of understanding of activities of different chemical species under high ionic strength, varying temperature, and pressure associated with treatment processes. Current aqueous solution models have limited ability to accurately predict precipitation kinetics under a wide range of temperatures, pressures, and in the presence of organic compounds and microbiological components beyond pure salt solution.

Impacts

As plants grow larger, the impacts of concentrate disposal on surface water or WWTPs will become more significant and may drive more facilities to seek alternatives to current approaches for brine management. This trend is likely to continue as regulations on concentrate disposal become more stringent, therefore potentially affecting nearly all desalination facilities in the United States. Advances in understanding of the physical and chemical properties of brines can provide the scientific basis for improved near ZLD technologies as well as more efficient operation of current ZLD technologies.

12.

RESEARCH NEEDS:

- **Develop** new thermodynamic and kinetic models or modify existing models based on water chemistry, temperature, pressure, and other operation-related conditions (e.g., non-steady-state operation, multistage, multiphase, mixture membrane module, membrane rotation, and clean-in-place schedule) to inform the design and operation of brine treatment, considering complex water chemistry (inorganic and organic constituents) under a broad range of operating conditions (TRL 2–4; 1–5 years).
- **Provide** scale inhibition methods by understanding the mechanisms of homogeneous and heterogeneous nucleation and crystallization (TRL 2–4; 1–4 years).
- **Accurately** predict nucleation and growth for scaling phases over a range of temperatures and pressures relevant to process conditions or in the presence of other colloidal, organic, or biological species (TRL 2–4; 1–5 years).
- **Develop** in operando monitoring methods to characterize nucleation, crystallization, and molecular-to-macroscopic properties of hypersaline solutions at different operating conditions and varying brine chemistry (TRL 2–4; 1–4 years).

5.5. Modular

Materials, Manufacturing, and Operational Innovations to Extend the Range of Cost-Competitive Treatment Components and Eliminate Intensive Pre/Post-Treatment.

M1.

Develop manufacturing innovations for on-demand production of water treatment system components.

Challenges

O&M of municipal water systems have cost and efficiency challenges associated with the site-specific aspects of many of their designs. Across multiple desalination and water treatment facilities analyzed in the Water-TAP3 tool, O&M activities accounted for 13 to 20 percent of the costs for water; the cost of electricity ranged from 14 to 47 percent. In addition to challenges posed by costs and operational efficiencies, the array of scales and uniqueness of systems also increases the complexity of regulatory approval and maintenance. Developing modular units to meet diverse water treatment capacity needs can take advantage of economies of scale in manufacturing to lower costs and energy intensities of water production for small-scale systems.

The emergence of 3D printing and other advanced manufacturing technologies have the potential to shorten supply chains and lower operating and maintenance costs of treatment facilities. The performance of components in water treatment operations that are made from materials that can currently be produced by advanced manufacturing processes is largely unknown. Given concerns regarding synthetic organic compounds as contaminants in water, research will be needed to evaluate leaching of organic compounds from novel 3D-printed components at relevant water chemistry conditions.

Impacts

This area of interest is national in scale because of its consideration of on-demand production of water treatment system components regardless of the source water or the particular treatment process. It is particularly relevant to medium and small systems where the economies of scale in manufacturing can have the greatest benefits. There is an opportunity to combine modularity with advanced manufacturing approaches to create pseudo-custom systems that are built to a common flowsheet but custom-sized to optimize material use and flow rates to specific building- or district-scale systems.

M1.

RESEARCH NEEDS:

- **Develop** production methods for versions of treatment system components (e.g., spacers, fittings, membrane module components, sensors) by 3D printing and other advanced manufacturing processes (TRL 3–4; 2–5 years).
- **Evaluate** components made from materials that can currently be 3D printed or produced by other advanced manufacturing processes with respect to their performance and the chemical and physical demands of treatment processes (TRL 2–4; 2–5 years).
- **Advance** the ability for on-demand production of components made from materials (e.g., elastomers and stainless steel) that cannot yet be inexpensively produced on demand (TRL 2–4; 3–5 years).

M2. Advance technologies that can improve the performance of building-scale on-site water treatment and reuse systems.

Challenges

This is already an active area of R&D, and greater deployment requires advances using demonstration-scale (i.e., higher TRL) systems. However, NAWI's emphasis on modular membrane systems is so intrinsic to these systems that it is highlighted as a priority research direction for the overall water technology community. There are also opportunities for lower-TRL research that can improve the performance of on-site water treatment systems; these include technologies for thermal energy recovery, engineering of the microbial community in membrane bioreactors, and understanding corrosion control and biofilm growth in building-scale water distribution. Advances in building-scale water treatment and reuse can also benefit from integration of advances in electrified processes that eliminate the need for chemical delivery and storage and autonomous treatment that enables improved remote monitoring and operation.

Impacts

On-site systems offer universal system O&M benefits of reduced conveyance. On-site systems further benefit urban systems by allowing greater density and not requiring infrastructure upgrades. Isolated systems also benefit from a reduced need for infrastructure hookups and potentially reduced environmental impacts associated with withdrawals and discharges.

M2. RESEARCH NEEDS:

- **Advance** methods to improve the efficiency and lower the costs of thermal energy recovery systems (TRL 3–4; 2–5 years).
- **Leverage** advances in understanding of the microbial community in membrane bioreactors to improve performance (TRL 3–4; 2–5 years).
- **Improve** understanding of corrosion and biofilm growth at the conditions of building-scale water distribution that are unique (e.g., higher T, longer stagnation) from those of city- and district-scale water distribution (TRL 3–4, 2–5 years).

5.6. Electrified

Electrifying Water Treatment Processes and Facilitating Clean Grid Integration

E1. Develop innovative technologies and materials to improve system efficiency and reduce the costs and energy demand of electrified processes.

Challenges

Water treatment and desalination are chemically intensive processes. Large amounts of chemicals are used during water treatment. From the Water-TAP3 analysis of the Carlsbad desalination plant, the O&M unit process costs for various chemical addition steps—ammonia addition, chlorination, carbon dioxide (CO_2) addition, lime softening, and sodium bisulfate addition—are around $12M per year. Electricity costs for accomplishing these steps account for about $5–6M per year.

Replacing chemical processes with electrical inputs can promote small scale, distributed water treatment by reducing the need for a chemical supply and minimizing the complexity of water treatment operations. Electrified processes introduce external fields and electrochemical reactions beyond the physicochemical mechanisms involved in conventional chemical water treatment processes.

Electrified processes encompass a broad range of technologies that are:

- Field-driven, such as high-voltage electric fields (e.g., electro-filtration, inactivation of bacteria and viruses), magnetic fields (e.g., high-gradient magnetic filtration), electromagnetic fields, high-gravity fields, ultrasonic waves, and microwaves
- Current-driven, such as electrocoagulation, electro-sorption, electro-oxidation, electrochemical reduction, and electrodialysis

In addition to water treatment, the applications of electrified processes include control of fouling and scaling and corrosion protection for process equipment. Early-stage research is needed in developing high-performance materials, understanding the fundamental science and modeling of electrochemical processes, enhancing process engineering, and optimizing system design.

Impacts

Replacing chemical processes with electrical inputs can promote small scale, distributed water treatment by reducing the need for a chemical supply and minimizing the complexity of water treatment operations. This has national relevance for any water treatment process that currently includes the use of chemicals.

E1.

RESEARCH NEEDS:

- **Develop** efficient and selective electrified processes (e.g., electrolysis, electrocoagulation, electrodialysis, bipolar electrodialysis, electrified membranes, electro-sorption, UV-light emitting diode [LED] AOP, electrochemical and electrocatalytic processes) for removal of contaminants (e.g., heavy metals, CECs), desalination, brine mining, elimination of chemical use or in situ chemical generation (e.g., coagulants, Cl_2, H_2O_2, caustic, acids) (TRL 2–4; 1–5 years).
- **Develop** new materials and process designs that expand electrified processes and simulation models of electrochemical processes for pretreatment (e.g., chemical-free scaling and fouling control with electromagnetic field and ultrasonic waves), treatment (e.g., contaminant removal, precision separation), and post-treatment processes (TRL 2–4; 1–5 years).
- **Develop** high-performance, robust, and inexpensive materials (e.g., electrodes, multifunctional membranes, electrocatalysts, electro-sorbents, IX membranes) for next-generation electrified and intensified processes (TRL 2–4; 1–5 years).
- **Advance** the development of chemical-free water softening systems that eliminate the need for a discharging location for sodium chloride brines from cation exchange (TRL 2–4; 2–5 years).
- **Couple** electrified technologies with other treatment processes to reduce energy intensity and improve system efficiency (e.g., combining UV-AOP and ozone [O_3] for intensified biological processes) (TRL 4; 1–3 years).

E2.

Evaluate electrified process through on-site monitoring, modeling, and material innovations.

Challenges

Electrified processes hold promise for energy-efficient, environmentally friendly, modular alternatives to traditional chemical treatment methods. However, the underlying complex physicochemical mechanisms that govern the performance of many electrified water treatment processes are not well understood. There is also a lack of foundational characterization methods to elucidate the mechanisms and real-time process monitoring and digital tools to optimize system performance and control system operation.

Impacts

Developing on-site monitoring, modeling, and material innovations will promote the use and reduce the costs of electrified processes, with relevance to any water treatment system currently utilizing chemicals.

E2.

RESEARCH NEEDS:

- **Develop** advanced characterization and real-time monitoring methods to elucidate the fundamental mechanisms and limitations of electrified processes in chemical water treatment processes (TRL 3–4; 1–4 years).
- **Develop** thermodynamic, transport, and kinetic models to investigate and improve the efficiency of electrified processes for water treatment for varying feed water quality and operating conditions (TRL 2–4; 1–5 years).
- **Understand** the electrochemical reaction mechanisms on material surfaces (e.g., electrodes, membranes, catalysts) to improve material preparation, electrode performance, and reactor design (TRL 2–4; 1–5 years).

E3.

Incorporate variable renewable energy into water treatment systems and leverage clean energy to replace chemical-intensive systems with electricity-intensive systems.

Challenges

Replacing chemically intensive processes with electrified processes provides a means of exploiting a variety of renewable and clean energy resources and temporal variations in electricity costs. Electrified treatment processes can facilitate small, remote desalination plants with affordable but variable renewable energy to deliver a sustainable water supply and electricity in areas with inadequate infrastructure. While water treatment processes have traditionally been designed to operate continuously, integration with variable renewable energy sources and demand response electricity markets will require all types of treatment systems to be operated flexibly with significant ramping capabilities. There is a research need for integration and optimization of electrified processes with renewable energy to increase system autonomy, modularity, and resilience.

Impacts

This area of interest is relevant for electricity grid-connected water treatment systems that could participate in demand response electricity markets to improve grid stability as well as distributed off-grid systems in areas with inadequate energy and/or water infrastructure.

E3.

RESEARCH NEEDS:

- **Develop** software control tools to integrate renewable and clean energy (e.g., wind, wave, solar, nuclear, thermal, deep-subsurface pressure-driven membrane operation) and electricity demand with electrified processes (TRL 4; 1–3 years).
- **Characterize** performance and mechanical integrity of materials when subject to variable operation and system shocks (TRL 4; 2–4 years).
- **Evaluate** and optimize membrane module components (e.g., glue lines and O-rings) to resist failure under periodic exposure to operational extremes (TRL 4; 2–4 years).

5.7. Technoeconomic Analysis and Life Cycle Analysis Opportunities

In addition to the challenges and TRL 2–4 research needs identified above regarding water treatment technologies, there are needs for technoeconomic assessment and life cycle assessment research. **These assessments can quantify the potential impact of potential research directions and assess the market feasibility of certain approaches.**

Challenges

- **Evaluate** the technical and economic feasibility (including market and demand investigation), process efficiency, resilience, robustness, product purity, environmental benefits, and potential risks of failure for intensified brine process.
- **Conduct** life cycle assessment and technoeconomic analysis of electrified treatment for different water quality characteristics, operating conditions, locations, and scales (e.g., centralized vs. decentralized, municipal vs. rural, remote locations), energy sources, chemical products generated, technologies used, safety concerns, and risks of handling hazardous chemicals.
- **Quantify** the potential benefits of materials with longer lifetimes or easier reuse and recycle.
- **Quantify** the costs and benefits of advanced manufacturing processes (e.g., 3D printing) for the production of water treatment components.
- **Assess** the potential for modular point-of-use treatment units for small water systems to break through regulatory and ownership barriers to implementation as components of a public water system.
- **Understand** the value proposition of developing disposable sensors for the municipal water supply industry.
- **Quantify** the synergies between renewable energy and electrified water treatment as well as the benefits gained in stability, reliability, and flexibility derived from electrification.

6. NEXT STEPS

This comprehensive and dynamic roadmap for low-TRL desalination and water treatment technologies for the Municipal End-Use Sector is intended to guide future R&D investments throughout the duration of the research program. NAWI's Master Roadmap will compile high-value, crosscutting themes across all PRIMA end-use water roadmaps, including this one, and will be categorized under the A-PRIME areas. In 2021, NAWI will begin implementing the crosscutting research priorities outlined in the Master Roadmap via requests for projects (RFPs) and a project selection process designed to align member needs with the Alliance's research and development efforts. The funded projects will represent the most impactful development opportunities that will ultimately motivate subsequent industry investments required to further enable the use of nontraditional water sources in a cost-effective manner.

Because the roadmap is a forward-looking document meant to guide NAWI throughout its existence, the Alliance will update it annually. Annual updates will also be critical to ensure that NAWI's roadmap evolves with the changing landscape of U.S. water treatment technologies, including the advancement in materials R&D, new processes, novel modeling and simulation tools, and expanded integrated data and analysis capabilities. Each aspect of the A-PRIME hypothesis, as well as the identified research priorities, will be regularly vetted with water treatment professionals from each PRIMA industry sector to ensure that it is a relevant pathway to advancing desalination and water treatment capabilities with nontraditional source waters. In successive roadmap iterations, the feedback will be used to assess the relevance of each research priority to the roadmap and evaluate progress toward achieving its goal of enabling a circular water economy for the Municipal Sector following the A-PRIME technology development hypothesis while considering all relevant pipe-parity metrics. NAWI will adjust its priorities and expand its available resources to maximize the impacts of its efforts.

The technology advancements developed by the NAWI research program are geared to help domestic suppliers of water desalination systems design and manufacture critical equipment, components, and small-modular and large-scale systems.

- Innovations from the NAWI Energy-Water Desalination Hub will promote energy-efficient, cost-effective, and resilient water purification, ensuring a secure supply of clean water for the nation and the world.

Appendix A: Acronyms

3D	Three dimensional
A-PRIME	Autonomous, Precise, Resilient, Intensified, Modular, and Electrified – NAWI R&D focus area
AOI	Areas of interest
AOP	Advanced oxidation process
As	Arsenic
AWPF	Advanced Water Purification Facility
AWWA	American Water Works Association
BAC	Biological activated carbon
CO_2	Carbon dioxide
CCL	Candidate contaminant list
CCP	Critical control point
CEC	Contaminants of emerging concern
CIP	Cleaning in place
Cl	Chlorine
Cr	Chromium
DOE	U.S. Department of Energy
DPR	Direct potable reuse
EPA	U.S. Environmental Protection Agency
EPWU	El Paso Water Utilities
GAC	Granular activated carbon
GAO	U.S. Government Accountability Office
g/L	Gram per liter
GWRS	Groundwater replenishment system
H_2O_2	Hydrogen peroxide
IoT	Internet of things

IPR	Indirect potable reuse
KBH	Kay Bailey Hutchinson desalination plant
kWh/m^3	Kilo-watt-hour per cubic meter
LCA	Life cycle analysis
LCOE	Levelized cost of electricity
LCOW	Levelized cost of water
LED	Light emitting diode
mg/L	Milligrams per liter
MF	Microfiltration
MGD	Million gallons per day
MWh/MG	Mega-watt hours per million gallons
MLD	Million liters per day
NAWI	National Alliance for Water Innovation Hub
NDMA	Nitrosodimethylamine
NF	Nanofiltration
NPR	Non-potable reuse
O_3	Ozone
OCWD	Orange County Water District
PFAS	Per- and polyfluoroalkyl substances
pH	Potential of hydrogen to specify the acid or base strengths
PRIMA	Power, Resource Extraction, Industry, Municipal, Agriculture End-Use sector focus for NAWI
RAC	Research advisory council
R&D	Research and development
RFP	Request for projects
RO	Reverse osmosis

RWPF	Raw water production facility
SCADA	Supervisory control and data acquisition
SiO_2	Silicon dioxide
SDWA	Safe Drinking Water Act
SWRO	Seawater reverse osmosis
TDS	Total dissolved solids
TEA	Technoeconomic analysis
TRL	Technology readiness level
TWh/year	Tera-watt hours per year
USGS	U.S. Geological Survey
UV	Ultraviolet
Water-TAP3	Water Technoeconomic Assessment Pipe-Parity Platform
WWTP	Wastewater treatment plants
ZLD	Zero-liquid discharge

Appendix B: NAWI A-PRIME Expanded Descriptions

Autonomous:

Current water treatment systems are designed to operate at nominally steady-state conditions, relying on human intervention to adapt to variations in water quality and correct failures in process performance. Simple, robust sensor networks coupled with sophisticated analytics and controls systems could enhance performance efficiency and process reliability. These more adaptable, smart systems could also minimize the need for on-site, manual interventions. Together, these innovations would significantly lower the cost of distributed, fit-for-purpose desalination systems.

Early-stage applied research can improve Internet of Things (IoT) infrastructure to meet the need for water treatment that is generalizable, secure, and resilient when managing sparse data and calibration errors. System identification and physics-based approaches can be used to develop reduced-order models and adaptive methods for closed-loop feedback control and optimization of interdependent water treatment processes. The developed controls approaches can be augmented with statistical and machine-learning-informed process monitoring techniques to diagnose system inefficiencies and faults. Data needs for process control and monitoring include temporal, nonlinear, stochastic, and uncertainty aspects of process parameters

Precise:

Current water treatment systems often rely on inefficient bulk separation processes to remove solutes that occur at trace levels. A more targeted treatment approach for trace contaminant removal can reduce the cost and energy intensity of treatment processes, while offering major reductions in system complexity and waste disposal costs. Precise separation or transformation of constituents also enhances the likelihood of profitable recovery and valorization of waste streams, offsetting the overall costs of desalination systems.

Early-stage applied research can improve the selectivity of materials and the efficiency of removal technologies for hard-to-treat or valuable-to-extract compounds (e.g., boron, hexavalent chromium, lead, nitrate, perchlorate, selenium, uranium, lithium, iodide). Simulation platforms can exploit molecular recognition principles in the design of highly selective materials. There is a need to synthesize and characterize these materials in high-throughput experimentation platforms. There is also a need to use process modeling and optimization tools to ensure that the high selectivity and affinity for target species, fast uptake kinetics, and efficient regeneration are fully exploited in continuous and intensified process designs. Such materials may become more cost-effective if they can tap into recent additive, gradient, and roll-to-roll manufacturing advances that lower production costs.

Resilient:

Current municipal water infrastructure relies on aging centralized water treatment, storage, and distribution systems that are energy-intensive, corroding, leaking, and costly to replace. In addition, key U.S. industries face complex logistics constraints in storing water and residuals and transporting them between remote locations, often via truck. While distributed treatment can reduce conveyance issues, these systems must function under conditions in which water quality, temperature, or water residence times undergo large fluctuations. Resilient water supply networks, adaptable treatment processes, and robust materials are needed if we are to realize the benefits of distributed, fit-for-purpose desalination systems.

Early-stage applied research to advance resilient water treatment and distribution systems will span molecular-scale to systems-scale research. Robust optimization techniques for materials and process design are needed to ensure compatibility with a wide variety of solution chemistries and accelerated materials. Aging platforms coupled with state-of-the-art in operando characterization tools can be used to test materials that resist corrosion and fouling in distributed desalination and conveyance systems. Step changes in treatment system reliability and resiliency can be enabled by the design of optimal sensor networks and analytics approaches that inform adaptive control techniques and allow processes to robustly operate over a wide range of feedwater quality levels. At the distribution system level, computationally efficient multiscale modeling and multi-objective optimization platforms are needed for water network designs that maximize reuse and minimize cost.

Intensified:

Current thermally driven brine management technologies are energy intensive, complex, and poorly suited for the modest flows of small-scale desalination systems. At the same time, there is an ongoing revolution in unconventional oil and gas development; expanded exploitation of inland brackish water resources; new regulatory requirements for effluent discharge at power generation, mining, and manufacturing facilities; and planning for future carbon storage in saline reservoirs, which are creating new demands for more efficient brine and concentrate management. Innovative technologies for brine concentration and crystallization would eliminate the need for brine conveyance, reduce dependence on finite injection well capacity, enhance water recovery from nontraditional sources, and lower energy intensity and cost of desalination facilities.

Early-stage applied research can focus on developing process alternatives to traditional, thermally driven brine management technologies, and materials innovations to improve the efficiency of existing processes. To concentrate brines between 75,000 and 200,000 mg/L TDS, there is a need for materials and manufacturing platforms that extend the pressure tolerance of RO membrane modules, process configurations that combine multiple driving forces, and systems that couple brine treatment with metals recovery and chemical synthesis. For higher-salinity brines treated by thermal processes, topology optimization and precision manufacturing methods can be paired to improve heat transfer in thermal processes, enabling efficient system integration with waste heat sources. Models of nucleation and crystalline phase growth that open new avenues for controlling scaling and promoting crystallization in energy-saving, small-scale units are also needed.

Modular:

Current seawater desalination systems use energy-efficient, and mass-manufactured RO membrane systems. When these same types of modules are used to desalinate organic and mineral-rich waters with higher fouling and scaling potential, energy consumption and maintenance costs increase. Furthermore, commercially available membranes are unable to separate ions of the same valence or remove low-molecular-weight neutral compounds from water. Finally, membranes are manufactured via poorly understood, highly nonequilibrium processes that limit property control and customization for specific feedwater compositions. Innovations in both membrane materials and manufacturing processes could vastly expand the range of water chemistries over which modular membrane systems are cost-competitive and potentially eliminate the need for intensive pre-treatment and post-treatment (e.g., multi-stage RO for boron removal). Further modularizing pre-treatment and post-treatment processes would increase reliability and reduce the costs of operating moderate-scale, distributed desalination systems.

Early-stage research is needed to advance the next generation of membrane materials and processes. These advances include the development of techniques that enable control of membrane properties during manufacturing, in operando materials characterization techniques that facilitate understanding of membrane performance under varying solute conditions, and manufacturing innovations that enable the scalable deployment of novel membrane materials in cost-competitive modules. It will also require process optimization models that explore the full range of process configurations, operating schema, and treatment train configurations for minimizing fouling and scaling while maximizing recovery. Advances in computational methods for materials design and selection, modeling platforms for accurately describing coupled mass transport and reactivity in porous media, materials processing approaches (e.g., additive, roll-to-roll, spray coating), and multiscale simulation tools for process optimization are needed to enable the necessary improvements in membrane flexibility and performance.

Electrified:

Current water treatment trains use large volumes of commodity chemicals that are high in embedded energy, expensive, and difficult to implement in distributed treatment systems. These processes are typically designed for steady-state operation, reducing their ability to ramp in response to fluctuations in water quality and the price of electricity. Replacing chemically intensive, steady-state processes with electrified and intermittently operated processes will reduce operating costs and provide a means of exploiting renewable energy resources and temporal variations in the cost of electricity. It will also promote small-scale, distributed water treatment by reducing the need for chemical supply and minimizing the complexity of water desalination operations.

Early-stage research to extend material and component longevity during intermittent process operation will reduce wear associated with rapid or frequent ramping. Process simulation models can be used to identify low-wear component designs and advanced manufacturing processes to realize them cost-effectively. To expand the number of electrified processes that might be ramped, there is a need to develop high-fidelity simulation models of electrochemical processes that include chemical, flow, faradaic, and non-faradaic effects in a variety of complex fluid compositions. These models can be applied in pre-treatment, treatment, and post-treatment processes to design materials and processes that improve performance consistency, eliminate chemical use, or generate chemicals (e.g., caustic, chlorine) in situ. There is a need for in situ methods for characterizing poorly understood process conditions, such as precipitation kinetics, flocculation dynamics, and ion distribution in boundary layers. Maximizing the potential of electrified treatment processes will also require the development of integrated energy-water economic models to quantify the synergies between these two systems as well as system improvements in stability, reliability, and flexibility.

Appendix C: DOE Water Hub Development Background

DOE's Water Security Grand Challenge is a White House-initiated, DOE-led framework to advance transformational technology and innovation to meet the needs for safe and affordable water and help secure the nation's water supplies. Using a coordinated suite of prizes, competitions, early-stage research and development funding opportunities, critical partnerships, and other programs, the Water Security Grand Challenge sets the following goals for the United States to reach by 2030:[71]

- Launch desalination technologies that deliver cost-competitive clean water
- Transform the energy sector's produced water from a waste to a resource
- Achieve near-zero water impact for new thermoelectric power plants and significantly lower freshwater use intensity within the existing fleet
- Double resource recovery from municipal wastewater
- Develop small, modular energy-water systems for urban, rural, tribal, national security, and disaster response settings

The Energy-Water Desalination Hub, or NAWI Hub, will support the goals of the Water Security Grand Challenge.[72] Specifically, the NAWI Hub will:

- Address water security needs for a broad range of stakeholders, including utilities, oil and gas production, manufacturing, agriculture, and states and municipalities;
- Focus on early-stage R&D for energy-efficient and low-cost desalination technologies, including manufacturing challenges, for treating nontraditional water sources for beneficial end-use applications and achieve the goal of pipe-parity;
- Establish a significant, consistent, and multidisciplinary effort (i.e., using a broad set of engineering and scientific disciplines) to identify water treatment challenges and opportunities;
- Enhance the economic, environmental, and energy security of the United States; and
- Lead to fundamental new knowledge to drive energy-efficient and low-cost technological innovations to the point that industry will further develop and enable U.S. manufacturing of these new technologies to be deployed into the global marketplace.

DOE is expected to support NAWI with $110 million in funding over five years, with an additional $34 million in cost-share contributions from public and private stakeholders.

Appendix D: Roadmap Teams

Cartography Team

Each PRIMA end-use sector was led by a small group of academic (3–4 people). This group is collectively known as the cartography team (total of 10 researchers) and identified challenges and research needs associated with the recovery and reuse of nontraditional waters. They are the primary authors for their end-use sector roadmap. The Master and Deputy Master cartographers synthesized high-value, cross-cutting themes across multiple end-use water roadmaps for the Master Roadmap.

Core NAWI Teams

Each PRIMA end-use cartography team was supported by a small group of subject matter experts (3–5 people) from industry, national labs, government, and academia; they contributed regularly to NAWI's water user roadmapping effort to help identify and establish future research priorities for NAWI, focusing particularly on the needs and opportunities of one assigned group of water users (municipal, agriculture, power, industrial, or resource extraction). Their activities included:

1. **Participating in roadmapping meetings:** Meeting twice a month to provide input, shape the direction of roadmapping activities, discuss recent developments, and review materials.
2. **Identifying key experts and practitioners to participate in roadmapping activities:** Recommending participants for interviews, workshops, and/or surveys as part of the roadmapping data collection process to obtain a wide array of industry insights.
3. **Providing insight on current and future needs for water treatment technologies:** Participating in meetings, (virtual and/or in-person) workshops, interviews, and/or surveys.
4. **Providing insights into quantitative data to support industry analysis, when possible:** Connecting NAWI researchers to sources of data that would facilitate baseline assessments.

Broader Teams

Each end-use cartography team was supported by a broader, more diverse group of subject matter experts (10–20 people); they contributed periodically to NAWI's water user roadmapping effort to help identify and establish future research priorities for NAWI, focusing particularly on the needs and opportunities of one assigned group of water users (municipal, agricultural irrigation, power, industrial, or resource extraction). Their activities included:

1. **Participating in roadmapping meetings:** Meeting monthly to provide input, shape direction of roadmapping activities, discuss recent developments, and review materials.
2. **Identifying other key experts and practitioners to participate in roadmapping activities:** Contributing to discussion of identifying participants for interviews, workshops, and/or surveys as part of the roadmapping data collection process.
3. **Providing insights on current and future needs for water treatment technologies:** Participating in meetings, (virtual and/or in-person) workshops, interviews, and/or surveys.
4. **Providing insights into quantitative data to support industry analysis, when possible:** Connecting NAWI researchers to sources of data that would facilitate baseline assessments.

Appendix E: Development of the NAWI Municipal Sector Technology Roadmap

Data Collection Process

The NAWI End-Use Sector Roadmaps were developed using a multi-step process coordinated by the NAWI end-use cartography teams. The key component of this process was a two-day virtual Technology Roadmapping Workshop—held in August 2020 and facilitated by Nexight Group—that included participants from industry, academia, national laboratories, and associations. Surveys and interviews with water and industry professionals were conducted in the months leading up to the workshop. Outputs from the surveys and interviews—including a comprehensive list of challenges and potential research solutions—were used to provide direction to the workshop sessions.

The result of these workshops was a refined list of industry-specific challenges and associated research solutions for each area of A-PRIME. These solutions were coupled with ongoing inputs from surveys, subject matter expert interviews and discussions, and other relevant documents to create the recommended list of research priorities in the End-Use Roadmaps. At several points during the roadmapping process, workshop participants, NAWI technical teams, and the DOE Advanced Manufacturing Office (AMO) reviewed the preliminary findings, intermediate, and final roadmap drafts prepared by NAWI and Nexight Group to further refine the content.

Activities Prior to the Technology Roadmapping Workshop

Online Survey

The NAWI teams and Nexight Group distributed an online survey to: 1) share a general understanding of water use and critical needs by sector; 2) identify critical barriers for nontraditional water treatment and reuse; and 3) identify early-stage applied research needs and opportunities (TRL 2–4) that will improve access and performance of nontraditional water desalination and treatment processes.

Between June and August 2020, the survey was sent to a diverse group of industry stakeholders covering all five of the end-use sectors. In the survey, participants were asked to provide their assessment and notional solutions to address these challenges. Additional optional questions were asked to gather targeted input based on the participant's sector (i.e., academia, industry, or government). The optional questions touched on the following areas: 1) decision criteria for using nontraditional water sources, 2) future water technology trends, 3) treatment system operations/design, and 4) regulatory conditions. The challenges and notional solutions identified from the survey findings were discussed and scrutinized during the technical workshops. Other findings were supplied to NAWI to further inform technical strategy and operations.

Subject Matter Expert Interviews

From June to August 2020, Nexight Group conducted more than 95 one-hour technical interviews with subject matter experts covering each of the 5 end-use sectors. These individuals were recommended by NAWI team members. These interviews were designed to engage stakeholders to 1) establish a baseline understanding of water use and minimum water quality for industry or business needs, 2) identify critical barriers for nontraditional water treatment and reuse, and 3) identify early-stage applied research needs that will improve access to and performance of nontraditional water desalination and treatment processes (e.g., by lowering the cost, decreasing energy use, increasing reliability, minimizing environmental impacts, maximizing resource recovery, removing contaminants). The challenges and notional solutions identified from the interview findings were discussed and scrutinized during the technical workshops. Other findings were supplied to NAWI to further inform technical strategy and operations.

Core and Broader Team Brainstorming

The end-use sector broader teams were engaged in an online brainstorming activity. They identified critical barriers for nontraditional water treatment and reuse and the research needs that will improve access to and performance of nontraditional water desalination and treatment processes. The challenges and notional solutions identified from these brainstorming sessions were discussed and scrutinized during the technical workshops. Other findings were supplied to NAWI to further inform technical strategy and operations.

Technology Roadmapping Workshop

Workshop Purpose

The NAWI roadmapping workshop was designed to identify potential research topics needed to address industry's water challenges and achieve the NAWI vision and pipe-parity goals. Each of the five NAWI end-use sectors had its own two-part, virtual roadmap workshop. Each workshop was built on the input collected from nearly 300 NAWI stakeholders via surveys, interviews, and working meetings conducted from June to October 2020.

Workshop Format

During the weeks of August 10 and 17, 2020, Nexight Group conducted 2 two-hour virtual sessions (using Zoom Video Communications) of up to 25 participants, with a homework assignment in between sessions. A minimum of 24 hours between the virtual sessions was provided to allow the completion of homework assignments. Prior to the workshop, participants reviewed a preliminary set of findings from previously collected input.

During the first of the two workshops, participants shared ideas through facilitated sessions. Structured brainstorming and critical analysis were used to refine the proposed list of NAWI research topics and identify additional research topics. After the first workshop for each end use, participants' homework consisted of ranking all potential research topics by a) probability of technical success, b) potential impact on NAWI goals, and c) timeframe for completion. These rankings were reviewed during the second workshop, and the research priorities were refined further based on feedback. After the second workshop, the raw data from the session was analyzed by Nexight Group and the cartography teams to arrive at a preliminary list of TRL 2–4 research priorities for each end-use sector. These topics were further reviewed, amended, and augmented by industry and expert engagement before being finalized in the five roadmap documents.

Workshop Outputs

The workshops were designed to deliver specific outputs necessary for the NAWI roadmapping process, including:

- Categorized sets of potential research topics for addressing water user challenges
- Ratings of each research topic in terms of probability of technical success and potential for impact on pipe-parity metrics
- Notional research timelines (near, mid, and long terms)

Preparation of the NAWI Technology Roadmaps

Research priorities in this roadmap are categorized under the six NAWI Challenge Areas (A-PRIME), which have been identified as critical to achieving a circular water economy. Using the information collected during the workshop and synthesized by cartography team, these preliminary findings were reviewed in September and October 2020 by the Core and Broader teams, NAWI Technical Teams, and DOE AMO staff. Concurrently, the Nexight Group and cartography teams compiled an initial draft (NAWI Internal Use Only) of the five roadmaps, which was reviewed by NAWI Technical Teams, Core and Broader Teams, and key DOE AMO staff in November and December 2020. Based on feedback from these sources, additional roadmap versions were developed and iterated on. A final public draft of the five NAWI roadmaps was then published.

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Appendix G: **References**

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