U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

# AMO Water and Wastewater RD&D

## December 7, 14, and 16, 2021 - Workshop Report

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## Disclaimer

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# Acronyms and Abbreviations

| | |
|---|---|
| AAAS | American Association for the Advancement of Science |
| AMO | U.S. Department of Energy's Advanced Manufacturing Office |
| BETO | U.S. Department of Energy's Bioenergy Technologies Office |
| BI | business intelligence |
| CEC | contaminants of emerging concern |
| CESMII | Clean Energy Smart Manufacturing Innovation Institute |
| CIDWT | Consortium of Institutes for Decentralized Wastewater Treatment |
| Comammox | complete ammonia oxidation |
| DOD | U.S. Department of Defense |
| DOE | U.S. Department of Energy |
| DOI | U.S. Department of the Interior |
| EERE | Energy Efficiency and Renewable Energy |
| EPA | U.S. Environmental Protection Agency |
| ESTCP | Environmental Security Technology Certification Program |
| FDA | U.S. Food and Drug Administration |
| GHG | greenhouse gas |
| GPS | global positioning system |
| HAB | harmful algal bloom |
| LBL | Lawrence Berkeley National Laboratory |
| LCA | lifecycle assessment |
| LLNL | Lawrence Livermore National Laboratory |
| MGD | million gallons per day |
| ML | machine learning |
| NAACP | National Association for the Advancement of Colored People |
| NAWI | National Alliance for Water Innovation |
| NEWS | Nexus of Energy and Water for Sustainability |
| NGO | non-government organization |
| NOAA | National Oceanic and Atmospheric Administration |
| NOWRA | National Onsite Wastewater Recycling Association |
| NRECA | National Rural Electric Cooperative |
| NREL | National Renewal Energy Laboratory |
| NRWA | National Rural Water Association |
| ORAU | Oak Ridge Associated Universities |
| ORISE | Oak Ridge Institute for Science and Education |
| PFA | perfluoroalkyl and polyfluoroalkyl substances |
| PNNL | Pacific Northwest National Laboratory |
| R&D | research and development |
| RCAC | Rural Community Assistance Corporation |
| RCAP | Rural Community Assistance Partnership |
| RD&D | research, development, and demonstration |
| RO | reverse osmosis |
| SC | U.S. Department of Energy's Office of Science |

| | |
|---|---|
| SFPUC | San Francisco Public Utilities Commission |
| SNL | Sandia National Laboratories |
| SRF | state revolving funds |
| TDS | total dissolved solids |
| TEA | technoeconomic analysis |
| TN | total nitrogen |
| TP | total phosphorous |
| TRL | Technology Readiness Level |
| USDA | U.S. Department of Agriculture |
| USGS | U.S. Geological Survey |
| WASH | water, sanitation, and hygiene |
| WATR | WAter TReatment interagency working group |
| WEF | Water Environment Federation |
| WHO | World Health Organization |
| WRAP | Water Reuse Action Plan |
| WRF | Water Research Foundation |
| WRRF | water resource recovery facilities |
| WWTP | wastewater treatment plant |
| WWTF | wastewater treatment facility |

# Executive Summary

The AMO Water and Wastewater RD&D Workshop Series took place over three days: December 7, 14, and 16, 2021 and gathered about 200 attendees across all sectors; from academia, industry, and utilities, to municipalities, tribes, national laboratories, and government.

**The following four key takeaways broadly encapsulate the several types of needs and opportunities** proposed by water and wastewater stakeholders to enable a more sustainable, resilient, and climate-adaptive wastewater treatment infrastructure:

1. **Impact and benefits assessments** including lifecycle assessments (LCAs) and technoeconomic analyses (TEAs) are needed to assess technology options, quantify benefits, gaps, and trade-offs, and understand the implications of water reuse and conservation practices. This involves collection and surveying relevant information from stakeholders, then evaluating, validating, and extrapolating the data for decision-making.
2. **Scalable and adaptable technology solutions** can meet a broad range of regional stakeholder needs and site-specific objectives in sustainable water management, circular water reuse, resource recovery, climate resilience, and watershed assessment and response.
3. **Robust, flexible, and reliable smart technologies** that can help stakeholders make informed decisions based on their specific regional needs in data-driven plant optimization, technology adoption, and long-term resource planning for infrastructural resilience and water circularity.
4. **Integrated technology demonstrations and co-development efforts** can reduce the cost and risk of implementing new water and wastewater management techniques while illustrating different technology adoption pathways and potential benefits to utilities and community decision-makers. Such piloting efforts can also help identify workforce development needs that would further facilitate technology adoption.

Participants worked across three parallel breakout groups to identify and prioritize specific RD&D needs for five different topic sessions, so-called "Thematic Areas." The breakout groups were designed to achieve a balance with respect to total participants, stakeholder types, and expertise areas. All groups expressed their respective sector needs, some of which were RD&D technology solutions at both early-stage and applied research levels, others of which called for broader action in areas like assessment, stakeholder engagement, and policy needs, all with varying levels of priority. These needs were thus categorized as different "Opportunity Types" as shown in **Table 1**.

Each Thematic Area lists priority needs and opportunities by **Key Opportunity Areas to bridge ideas across the breakout groups**. This first table lists these Key Opportunity Areas.

*Table 1: **Key Opportunity Areas** for each thematic area, which comprise the prioritized Opportunities across all breakout groups. Each specific need or opportunity listed in this report is categorized by one or more Opportunity Types.*

| Thematic Area | Key Opportunity Areas | Opportunity Type | | | | |
|---|---|---|---|---|---|---|
| | | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| 1. Municipal Systems | 1.1. Strategies to optimize distribution, collection, and treatment systems | | ■ | ■ | ■ | |
| | 1.2. Circular economy and resource recovery market opportunities | | ■ | ■ | ■ | ■ |
| | 1.3. Demonstrations and decision support tools to de-risk technology adoption | | ■ | ■ | ■ | |
| | 1.4. Environmental impact and resilience assessments | | ■ | ■ | | |
| 2. Agricultural Systems | 2.1. Risk and scalability analyses of sustainable water management approaches | ■ | | ■ | | ■ |
| | 2.2. Robust guidance and decision support for agricultural sustainability | | ■ | ■ | ■ | |
| | 2.3. Resource recovery and conservation techniques | ■ | ■ | ■ | | |
| | 2.4. Low-cost decentralized water treatment technologies | | ■ | ■ | ■ | |
| | 2.5. Collaborative circular water economy model demonstrations | | ■ | ■ | ■ | |
| 3. Systems for Underserved Communities | 3.1. Impact analyses and benefits assessments | | | ■ | ■ | |
| | 3.2. Workforce support and training initiatives | | | | ■ | ■ |
| | 3.3. Advocacy and community mobilization support | | ■ | ■ | ■ | ■ |
| | 3.4. Design of low-cost point-of-use water treatment technologies | | | | | |
| 4. Artificial Intelligence, Data Analytics, and Sensors | 4.1. Data-driven modeling solutions for water facility management and process control | | ■ | | | |
| | 4.2. Distributed sensors for early detection and response | | ■ | ■ | ■ | |
| | 4.3. Methods to improve sensor reliability and data accuracy | | ■ | | | |
| | 4.4. AI/ML-ready data architectures to support decision-making | | ■ | ■ | ■ | |
| 5. Resilience and Circular Economy | 5.1. Robust AI capabilities for extreme event interpretation and prediction | ■ | ■ | ■ | | |
| | 5.2. Locality-specific decision-making tools and climate adaptation planning | ■ | ■ | ■ | ■ | |
| | 5.3. Cross-sector water monitoring framework for informed decision-making | | ■ | ■ | ■ | |
| | 5.4. Macroeconomic impact studies of circular economy transitions | | ■ | ■ | | |
| | 5.5. Maximizing the value of water reuse and resource recovery | | | ■ | | |

Across the five Thematic Areas, several of the specific opportunities are interrelated, or share common objectives. These "Idea Clusters" are listed in the **Conclusion**.

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# Introduction

In December 2021, the Advanced Manufacturing Office within the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) convened experts, practitioners, and water end-users across the water and wastewater sectors, over three days, to (1) understand challenges to achieve a modern, sustainable, resilient, and climate-adaptive water and wastewater treatment infrastructure, (2) advise analysis and RD&D needs, and (3) expand stakeholder and funding opportunity reach. On Day 1 participants listened to invited speakers from across the government, non-profits, industry, and academia before contributing their own insight during the breakout sessions held on Day 2 and 3 (see **Appendix A. Workshop Structure and Agenda**).

## Thematic Areas

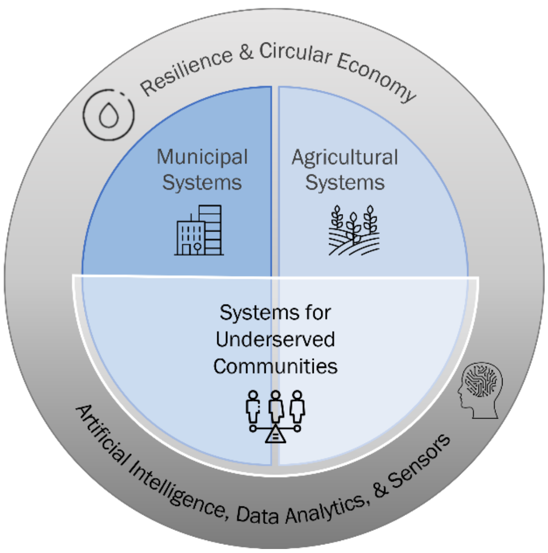



*Figure 1: Schematic depicting relationship between the thematic area topic sessions*

During each breakout session, attendees provided inputs on unmet research, development, and demonstration (RD&D) needs associated with one of five topical **Thematic Areas**. The first four themes listed below were informed by existing projects and internal DOE conversations, whereas the fifth theme was crowd-sourced and voted upon by workshop attendees. These five Thematic Areas can be thought about in an interrelated way. As depicted in **Figure 1**, the first three session themes reflect stakeholder topics, with underserved communities crosscutting the municipal and agricultural systems. The last two sessions listed below encompass tools and frameworks needed to build out these systems.

- **Municipal Systems**—Cities at all scales can achieve circular economy and sustainability goals through low-risk, resource-efficient wastewater treatment systems; strategies to target inefficiencies in existing distribution and collection systems; and pathways to recover energy and high-value products including biogases and biosolids.
- **Agricultural Systems**—Farms, ranches, and homesteads, which rely on a diverse range of water sources for irrigation, pesticide applications, fertilizing, and crop production, can reduce their environmental footprint by implementing water reuse techniques, employing methods to reduce nutrient runoff and prevent algal blooms, and displacing fossil energy-based fertilizers through biomass valorization and other wastewater treatment practices.

- **Systems for Underserved Communities**—Small, geographically dispersed, or under-resourced communities (including those in rural, urban, and tribal settings) which may not benefit from the economies of scale associated with large centralized systems, can benefit from economic assistance and access to water reuse funding mechanisms, social and environmental advocacy support, and affordable "plug-and-play" technology options with reduced implementation risk and low energy requirements.
- **Artificial Intelligence, Data Analytics, and Sensors**—Sensors, data analytics, and artificial intelligence can help to optimize processes, improve process stability, support decision-making, and inform scenario planning for resilient infrastructure and sustainable water management.
- **Resilience and Circular Economy**—This topic was specifically crowdsourced by workshop participants to emphasize the need for next generation water systems infrastructure to prepare for the impacts of climate change and enable a circular water economy to account for changes in water demand and usage by sector and end-use application.

## Opportunity Types

Although the workshop was primarily designed to solicit ideas for new RD&D activities within the scope of DOE-AMO's water and wastewater portfolio, participants articulated a broad range of needs, possibilities, and potential solutions for creating more sustainable, equitable, resilient, and affordable water systems. From each thematic topical session, specific challenges were summarized, and opportunities identified. These opportunities are presented under the Thematic Area in which they were discussed and are categorized by one or more of the following color-coded **Opportunity Types** as shown below in Table 2. It should be noted that the first two opportunity types are directly associated with Technology Readiness Level (TRL) indicators. The other opportunity types listed are not associated with TRL designations.

*Table 2: Each RD&D need or opportunity listed is categorized by at least one of the following five **Opportunity Types**.*

| | |
|---|---|
| (light blue) | **Early-Stage Research Activities (TRL 0-2):** Fundamental or early-stage research activities that are out-of-scope for DOE-AMO's RD&D programs but are otherwise under the purview of adjacent federal agencies.[1] |
| (orange) | **Applied RD&D Activities (TRL 3-6):** Research, development, and demonstration activities ranging from applied research to small-scale pilots in relevant environments. These RD&D activities are within scope of AMO's water and wastewater project portfolio. |
| (green) | **Assessments & Problem Analyses:** Supporting assessments to analyze or measure specific problems and evaluate the impact of proposed solutions. |
| (dark blue) | **Stakeholder Engagement:** Activities that promote increased collaborative stakeholder engagement and private-private partnerships through the deployment, demonstration, and implementation of regional prototype systems and solutions for wastewater treatment and water resource recovery. |

| | |
|---|---|
| | **Policy Solutions:** Ideas, strategies, or principles of action that are the basis for making decisions, determining future actions, or informing regulatory actions. These items are beyond DOE-AMO's scope. |

# 1. Municipal Systems

Municipalities require a significant amount of energy and resources to transport and treat drinking water and wastewater. Utilities can supplement traditional activated sludge processes with advanced wastewater treatment systems to remove nutrients and recover valuable products, but these processes are typically expensive and energy intensive. Achieving circular economy and sustainability goals will require the development of low-risk resource-efficient wastewater treatment systems, strategies to target inefficiencies in existing distribution and collection systems, and pathways to recover energy and high-value products including biogases and biosolids.

## Problem Statements

During the breakout group discussions of specific R&D needs, workshop participants provided additional information regarding specific challenges and issues regarding specific R&D needs in municipal water and wastewater treatment and some potential proposed solutions.

***To achieve sustainability and circular economy needs, municipal wastewater treatment systems require maintenance and retrograding, however, upfront costs are high.***

Many low-resource, small-scale rural operators struggle to finance the high capital costs of water infrastructure and wastewater resource recovery technologies. Though municipal wastewater treatment systems and infrastructure are designed to last for decades, it is not clear how these systems can adapt or evolve to meet future needs for climate challenges and circular economy approaches. Aside from access to funding mechanisms to support implementation and pressures that keep customer bills low, maximizing the value of municipal wastewater system investments will require continuous tracking of the ongoing implementation of these technologies to gather best practices, lessons learned, and other useful information to help reduce technology implementation risk.

***Utility managers are risk-adverse, focus on system reliability and regulatory compliance, and shy away from new technologies that prioritize sustainability and a circular economy without external pressure.***

Utility managers and operators especially of small-scale water resource recovery facilities (WRRFs) are primarily focused on system reliability and compliance with permitting requirements and are generally less concerned with carbon reduction and energy management strategies. Well-researched analysis studies—or tools to make wholistic operating assessments—can help identify where efficient system improvements can be made to promote trust and facilitate policy/regulatory discussions.

***Funding opportunities provide funds to allow for testing of new sustainable technologies, yet the funding process is generally not accessible for wastewater treatment facilities (WWTFs; also known as wastewater treatment plants, WWTPs).***

Municipalities can apply for funding to demonstrate new municipal wastewater treatment systems, but the overall process is typically long and frustrating. Additionally, available funding opportunities are sporadic and irregular. Most funding opportunities to pilot new technologies includes cost sharing requirements, and utility boards and managers are reluctant to fund even a portion of the pilot where the primary beneficiary is seen as the for-profit technology developer. Alternative financing mechanisms could help accelerate the time to implement new municipal systems to achieve circular economy and climate change adaptation objectives.

***Nutrient and contaminant removal techniques could intensify energy requirements and carbon emissions.***

Emerging regulations designed to combat nutrient pollution[2] and methods for treating contaminants of emerging concern (CECs) may counteract decarbonization goals and result in higher energy and emissions outputs caused by the increased use of nutrient and contaminant removal technologies in wastewater treatment. This points out the importance of recognizing energy efficiencies and inefficiencies when designing new treatment systems.

***Utilities face long timetables to validate new technologies for municipal systems.***

The implementation of new or novel municipal wastewater treatment systems and infrastructure requires a time- and resource-intensive process of validation and testing. Additional demonstration and deployment scale studies could expedite this process and enhance novel technology adoption.

## Opportunities

The following table organizes related ideas presented above by Key Opportunity Area, specific Opportunities, and overlapping Thematic Areas (represented by icons).

*Table 3: **Municipal Systems**' prioritized Opportunities with other overlapping Thematic Areas.*

| Key Opportunity Areas | Opportunities | Thematic Area | | | | |
|---|---|---|---|---|---|---|
| | | MUNICIPAL SYSTEMS | AGRICULTURAL SYSTEMS | SYSTEMS FOR UNDERSERVED COMMUNITIES | AI, DATA ANALYTICS & SENSORS | RESILIENCE & CIRCULAR ECONOMY |
| **1.1 "Strategies to optimize distribution, collection, and treatment systems** | Develop analysis and tools that incorporate the lifecycle to inform facility- and regional-level efficiency gains | ● | ● | | ● | ● |
| | Define typologies of water treatment systems to prioritize site-specific sustainability objectives | ● | | ● | ● | ● |
| | Develop real-time wastewater collection system surveillance to support operational decision-making and optimization at treatment plants | ● | | ● | ● | ● |
| **1.2 Circular economy and resource recovery market opportunities** | Identify economic opportunities, market drivers, and applications for WRRF recovered products, including reclaimed water | ● | | | | ● |
| | Develop modular carbon diversion, low-energy treatment, and nutrient recovery technologies in WRRFs | ● | | | | ● |
| | Demonstrate co-benefits of wastewater heat recovery in urban communities | ● | | | | ● |
| **1.3 Demonstrations and decision support tools to de-risk technology adoption** | Conduct full-scale, long-term demonstration pilots of emerging treatment technologies to demonstrate efficacy and efficiency gains | ● | | ● | ● | |
| | Design scalable and adaptable digital tools to enable modeling, visualization, and optimization of current full-scale treatment processes | ● | | | ● | |
| **1.4 Environmental impact and resilience assessments** | Conduct a comparative analysis of centralized and distributed water treatment systems | ● | | | | |
| | Design and develop novel wastewater treatment solutions and water reuse opportunities for rising total dissolved solids (TDS) concentrations based on comprehensive environmental and economic assessments | ● | | | | |
| | Analyze the resiliency needs of interconnected water-energy systems | ● | | ● | | ● |

The following section provides detailed information on the Municipal Systems breakout sessions' Opportunity Areas and their associated Opportunities that align with different activity Opportunity Types: early-stage research (in light blue), applied R&D (in orange), assessment and problem analyses (in green), stakeholder engagement (in dark blue), and policy (in yellow).

*Table 4: **Municipal Systems**' Opportunity Areas and Opportunities color-coded by Opportunity Type.*

| Opportunity Area 1.1: **Strategies to optimize water distribution, collection, and treatment systems**—Provide solutions to help operators optimize the overall efficiency of water distribution, collection, and resource recovery systems to reduce waste and achieve decarbonization goals. | | | | | |
|---|---|---|---|---|---|
| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **1.1.1. Develop analysis and tools that incorporate the lifecycle to inform facility- and regional-level efficiency gains**—Many water treatment plants and WRRFs (in particular, small-scale systems)[3] lack the flexibility and resources to quantify the energy intensity and carbon emissions of their operations. Robust lifecycle data[4] and efficiency assessment tools could help utility managers pinpoint and implement opportunities for improving facility-level system efficiencies and cost savings. For some regions, lifecycle and other assessments could help inform regional-level water treatment decisions and strategies such as whether to pursue centralized or distributed collection systems. | | | | | |
| **1.1.2. Define typologies of water treatment systems to prioritize site-specific sustainability objectives**—Develop typologies of different water treatment facilities (permits, influent characteristics, climate, system size, etc.) to help identify the specific technology and water infrastructure configuration options that are best suited to achieve energy reduction and production goals. | | | | | |
| **1.1.3. Develop real-time wastewater collection system surveillance to support operational decision-making and optimization at treatment plants**—Real-time data collection across wastewater systems and infrastructure can provide wastewater treatment facilities with critical insights including flow, physical characteristics, and chemical measurements needed to support decision-making and optimize wastewater treatment processes.[5] Stakeholder engagement efforts should explore systems-level approaches for integrating sensors and machine learning (ML) to help water utility companies reduce GHG emissions and improve the efficiencies of their water distribution systems. Integrated sensors could help optimize water pumping operations,[6] monitor pump health, increase water-to-wire efficiencies, detect leakages, and reduce lifetime maintenance costs.[7] | | | | | |

| **Opportunity Area 1.2: Circular economy and resource recovery market opportunities**—Promote the adoption of circular economy principles for water resource recovery facilities (WRRFs) by demonstrating techniques to treat and reuse wastewater while recovering nutrients, renewable energy, and other valuable resources for use in secondary applications. | | | | | |
|---|---|---|---|---|---|
| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **1.2.1. Identify economic opportunities, market drivers, and applications for WRRF recovered products**—To encourage the valorization of clean water, nutrients, energy, and other products recovered from municipal water resource recovery facilities (WRRFs), research efforts should quantify the economic opportunities for reusing treated wastewater[8] and prioritize potential markets and applications for recovered products. A consensus-based roadmap focused on the circular economy of wastewater systems could help guide research and pilot-scale demonstrations for maximizing the value of recovered waste stream products and inform strategies for the long-term evolution of resource recovery technologies. Product certifications like U.S. regulatory grades and standards[9] could help facilitate valorization efficiency and build confidence in product quality for both users and producers. | | | ■ | | ■ |
| **1.2.2. Develop modular carbon diversion, low-energy treatment, and nutrient recovery technologies in WRRFs**—Carbon diversion, low-energy treatment and nutrient recovery technologies including influent filtration, anaerobic primary and secondary wastewater treatment, and co-digestion can help WRRFs achieve decarbonization goals. Influent filtration redirects biodegradable materials from wastewater into separate streams to remove nutrients, recover water, and reduce embodied energy.[10] Newly discovered bacteria, comammox (i.e., complete ammonia oxidation), can reduce the energy required for nitrification in the wastewater treatment process. Efforts should focus on demonstrating full-scale modularized carbon diversion, low-energy treatment, and nutrient recovery technologies to quantify energy savings benefits toward promoting their broader adoption across the water and wastewater sector. | | ■ | | ■ | |
| **1.2.3. Demonstrate co-benefits of wastewater heat recovery in urban communities**—Pilot demonstration projects[11] in urban communities should demonstrate the co-benefits of recovering thermal energy from wastewater in collection systems and at wastewater treatment plants. Wastewater heat recovery could satisfy domestic heating demands and increase the overall share of renewable energy. | | ■ | | ■ | |

**Opportunity Area 1.3: Demonstrations and decision support tools to de-risk technology adoption**—Provide full-scale demonstration tests and modeling tools to help municipal systems operators and decision-makers conceptualize and adopt advanced energy efficient and advanced water resource and recovery technologies.

| Opportunities | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
|---|---|---|---|---|---|
| **1.3.1. Conduct full-scale, long-term demonstration pilots of emerging treatment technologies to demonstrate efficacy and efficiency gains**—Full-scale demonstrations of emerging water resource and recovery technologies such as testbed facilities for experimenting under realistic operating conditions could provide critical insights into efficacy of new technologies and potential water and energy efficiency gains.[12] Demonstration-scale buildings and communities with integrated water systems could be outfitted with cost-effective sensors, actuators, and modular water resource and recovery technologies to serve as a platform to help utilities—especially those in underserved rural communities—to save money, reduce energy demand, and increase infrastructure resilience. These insights could help de-risk the adoption of systems-level water treatment technologies with greater decarbonization potential compared with individual components or techniques that only promise to deliver incremental efficiency gains. | | | | | |
| **1.3.2. Design scalable and adaptable digital tools to enable modeling, visualization, and optimization of current full-scale treatment processes**—Data-driven modeling tools[13] can help operators to conceptualize systems-level impacts of implementing new water resource and recovery technologies, deployment configurations, and accompanying interfaces before fully committing to new water infrastructure decisions. Robust modeling tools will require the collection of data from various configurations and sizes of existing WRRFs. In the long-term, these modeling tools could integrate with risk-based financing to support the development of novel water-energy joint concepts. | | | | | |

| Opportunity Area 1.4: **Environmental impact and resilience assessments**—Assess the long-term economic, environmental, and resilience implications of water resource and recovery strategies. | | | | | |
|---|---|---|---|---|---|
| Opportunities | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **1.4.1. Conduct a comparative analysis of centralized and distributed water treatment systems**—To support technology adoption for utility companies and water infrastructure decision-makers, efforts should quantify the emissions and energy trade-offs for installing and maintaining different scales of wastewater treatment and collection[14] which would include an analysis of the embedded carbon in the physical infrastructure of water systems (e.g., concrete production, steel production). These insights could also provide the impetus for developing improved methods for mitigating corrosion and extending the useable lifetime of the physical infrastructure, reducing both lifetime emissions and long-term maintenance requirements. | | | ■ | | |
| **1.4.2. Design and develop novel wastewater treatment solutions and water reuse opportunities for rising total dissolved solids (TDS) concentrations based on comprehensive environmental and economic assessments**—TDS concentrations in wastewater will continue to rise and as more municipalities implement water reclamation, reuse, and conservation strategies. Research and development efforts must address TDS in economically and environmentally viable ways and explore opportunities and tradeoffs of using treated wastewater for different applications, such as agriculture, mining, municipal needs, and industry. | | ■ | ■ | | |
| **1.4.3. Analyze the resiliency needs of interconnected water-energy systems**—As more interconnections emerge across water-energy-transport-gas systems, municipalities and utilities must ensure their supply chains are resilient against extreme weather events and cyber-incidents. Research efforts should help stakeholders understand the most significant threats to infrastructure and information systems and how to prevent incidents from cascading across the supply chain. | | | ■ | | |

## Additional Needs and Opportunities – Municipal Systems

The following additional needs and opportunities did not receive a significant number of votes during the prioritization exercises, or lacked sufficient contextual information as needed to merit their convergence or inclusion with similar ideas:

- Source separation and treatment of urine for nutrient management
- Cohort training and learning opportunities to realize energy efficiency benefits from optimizing operations while remaining compliant with permit requirements
- Methods for measuring carbon offsets toward carbon neutrality
- Two-way communication strategies for grid response and flexible load management control

- R&D of cyanobacterial nutrient removal techniques to evaluate energy and carbon trade-offs and address the challenge of new effluent regulatory limits on nitrogen and phosphorus

# 2. Agricultural Systems

As one of the most water-intensive sectors in the world, particularly in the western U.S., agriculture expends freshwater resources for irrigation, pesticide applications, fertilizing, and other crop production purposes. To improve water efficiency and conserve resources, agricultural users can incorporate novel approaches in water treatment, water conveyance, and solids management to recycle water and recover nutrients. Farms can lower their environmental footprint in a variety of techniques. Those include water reuse, applying technologies that reduce nutrient runoff and prevent downstream algal blooms, and displacing fossil energy-based fertilizers through wastewater component valorization.

## Problem Statements

During the breakout group discussions of specific R&D needs, workshop participants provided additional information regarding challenges and issues regarding R&D needs in agricultural systems and some potential proposed solutions.

***High cost of investments with unknown return for the farmer are perceived as high risk and thus leads to low interest in adoption of technologies and practices that prioritize resource recovery and sustainable water management.***

Uncertain or unstable factors such as crop prices, soil erosion, droughts, and moisture stress are among a few reasons for highly variable gross profit margins in crop production—in addition to volatile agricultural commodity prices. This perceived risk is compounded by the relative low cost of water in many agricultural regions and the comparatively prohibitive cost of modular systems for resource recovery, solids management, and water reuse[15]. However, modular systems could be viewed as much more affordable if the true value of water is considered.

***Water quantity and quality demand, supply, and disposal needs are unique.***

Due to regional differences in water access, crop-specific requirements, soil type and health, profit margin risk, geological characteristics, and climate conditions, there are no universally applicable methods for wastewater treatment and water reuse. In some cases, farmers may be less likely to invest in water reuse and resource recovery methods if they have greater access to clean water or live in less drought-prone areas. Data-driven methodologies could help users match their specific water management needs to affordable fit-for-purpose solutions.

***Knowledge of human and environmental health risks associated with water reuse for agriculture is incomplete or unknown.***

The agricultural industry and regulatory decision-makers are reluctant to implement water treatment and reuse technologies without a clear understanding of the risk level associated with micropollutants[16], contaminants of emerging concern[17], and other potentially dangerous substances from wastewater (consisting of wastewater, greywater, stormwater, and rainwater) that evade current treatment techniques. Substantiating the requirements and regulations for treating recycled water to ensure agricultural products are safe for consumption may also help combat negative perceptions about water reuse.[18]

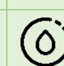
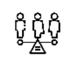
***"Water rights" doctrines conflict with sustainable water use practices.***

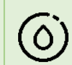
Some state and local doctrines[19] require unused water to be recovered and reallocated by the state, thereby disincentivizing sustainable water practices. The implementation of new agricultural technologies requires equal attention for balanced policy measures that encourage water reuse without infringing upon water rights.

## Opportunities

The following table organizes related ideas presented above by Key Opportunity Area, specific Opportunities, and overlapping Thematic Areas (represented by icons).

*Table 5: **Agricultural Systems**' prioritized Opportunities with other overlapping Thematic Areas.*

| Key Opportunity Areas | Opportunities | Thematic Area | | | | |
|---|---|---|---|---|---|---|
| | | MUNICIPAL SYSTEMS | AGRICULTURAL SYSTEMS | SYSTEMS FOR UNDERSERVED COMMUNITIES | AI, DATA ANALYTICS & SENSORS | RESILIENCE & CIRCULAR ECONOMY |
| **2.1. Risk and scalability analyses of sustainable water management approaches** | Study the risks associated with micropollutants on food quality and safety | |  | | | |
| | Evaluate the infrastructural and environmental implications of large-scale expansion of water reuse practices | |  | | | |
| | Conduct lifecycle and risk assessments on biosolids reuse applications | |  | | |  |
| **2.2. Robust guidance and decision support for agricultural sustainability** | Develop data-driven methods for prioritizing locality-specific water management decisions | |  |  | | |
| | Identify the optimum conditions and locations to install water reclamation technologies | |  | | |  |
| **2.3. Resource recovery and conservation techniques** | Conduct regional prototype demonstrations of nature-based solutions for reducing run-off and nutrient losses | |  | | |  |
| | Apply precision agriculture practices to modular resource recovery technologies | |  | | | |
| **2.4. Low-cost decentralized water treatment technologies** | Develop cost-effective approaches to achieve target mineral composition in recycled water | |  | | |  |
| | Determine the efficacy and benefits of distributed water treatment systems to add capacity or redundancy to centralized systems | |  |  | |  |
| | Demonstrate scalable water reuse approaches in small and under-resourced communities to address key implementation barriers | |  |  | | |

| Key Opportunity Areas | Opportunities | Thematic Area: MUNICIPAL SYSTEMS | AGRICULTURAL SYSTEMS | SYSTEMS FOR UNDERSERVED COMMUNITIES | AI, DATA ANALYTICS & SENSORS | RESILIENCE & CIRCULAR ECONOMY |
|---|---|---|---|---|---|---|
| **2.5. Collaborative circular water economy model demonstrations** | Design a closed-loop system for wastewater treatment, energy and nutrient recovery, and carbon capture | |  | | |  |
| | Build public-private relationships to demonstrate successful regional-level circular water economy pathways | |  | | | |

The following section provides detailed information on the Agricultural Systems breakout sessions' Opportunity Areas and their associated Opportunities mapped out in color by different activity Opportunity Types.

*Table 6: **Agricultural Systems**' Opportunity Areas and Opportunities color-coded by Opportunity Type.*

**Opportunity Area 2.1: Risk and scalability analyses of sustainable water management approaches**—Evaluate the potential impact of transitioning toward sustainable and circular economy water management approaches to reduce health risks and ensure alignment with decarbonization objectives.

| Opportunities | EARLY-STTAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
|---|---|---|---|---|---|
| **2.1.1. Study the risks associated with micropollutants on food quality and safety**—Conduct analyses of reclaimed water that originate from municipal wastewater sources to detect the presence of micropollutants, antibiotics, and various contaminants of emerging concern (perfluoroalkyl and polyfluoroalkyl substances [PFAS], etc.), and examine any potential health concerns associated with the quality of produce or grains. | ■ | | | | |
| **2.1.2. Evaluate the infrastructural and environmental implications of large-scale expansion of water reuse practices**—Research efforts should examine how the widespread adoption of sustainable water treatment and reuse practices for agricultural purposes (including the impact of regulations) will affect both natural ecosystems and downstream infrastructure including the points where recycled waters are diverted from discharge. | | | ■ | | ■ |
| **2.1.3. Conduct lifecycle and risk assessments on biosolids reuse applications**—Conduct a comparative lifecycle assessment to understand the emissions and energy footprint of the recovery and reuse of biosolids as a displacement for synthetic and fossil energy-based fertilizers for agricultural use and the implication of regulatory requirements.[20] | | | ■ | | ■ |

**Opportunity Area 2.2: Robust guidance and decision support for agricultural sustainability**—Provide farmers with guidance and decision support to optimize water infrastructure configuration options based on locality-specific needs.

| Opportunities | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
|---|---|---|---|---|---|
| **2.2.1. Develop data-driven methods for prioritizing locality-specific water management decisions**—Create a structured framework for characterizing locality-specific systems to help inform and prioritize regional-level sustainable water resources management needs and goals. | | ■ | ■ | | |
| **2.2.2. Identify the optimum conditions and locations to install water reclamation technologies**—Efforts should focus on outcomes that provide users with guidance and support on the ideal conditions and locations[21] for installing technologies that harvest or collection rainwater, groundwater (e.g., aquifer recharge), and atmospheric water to supplement primary irrigation water sources. | | | ■ | ■ | |

**Opportunity Area 2.3: Resource recovery and conservation techniques**—Demonstrate environmentally friendly methods for reducing nutrient run-off and maximizing resource recovery opportunities.

| Opportunities | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
|---|---|---|---|---|---|
| **2.3.1. Assess regional nature-based solutions for reducing run-off and nutrient losses**—In addition to reducing agricultural run-off, nature-based solutions such as engineered wetlands may also deliver several co-benefits such as carbon sequestration, increased biodiversity, wildlife habitat restoration, environmental remediation, fewer nitrous oxide emissions, and lower reliance on synthetic fertilizers.[22] The Federal government could eventually play a key role in facilitating collaborative partnerships to conduct regional prototype demonstrations of nature-based solutions that meet circular water economy objectives.[23] | | ■ | ■ | ■ | |
| **2.3.2. Apply precision agriculture practices to modular resource recovery technologies**—Develop modularized[24] resource recovery technologies that rely on precision agriculture methods (i.e., data-driven tools and technologies such as sensors, GPS, imagery technology) to efficiently recover nutrients[25] and energy[26] from applications including agricultural processing facilities and food waste across the value chain. | | ■ | | | |

**Opportunity Area 2.4: Low-cost decentralized water treatment technologies**—Develop and demonstrate water treatment technologies that are modular, low-cost, and scalable to meet the specific needs of small and under-resourced communities.

| Opportunities | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
|---|---|---|---|---|---|
| **2.4.1. Develop cost-effective approaches to achieve target mineral composition in recycled water**—Farms that rely on recycled tailwater, brackish groundwater, and wastewater need inexpensive methods for reducing the salt content (i.e., sodium, chloride, boron), and adding magnesium, calcium, and other ions that are essential to plant growth. | | ■ | | | |
| **2.4.2. Determine the efficacy and benefits of distributed water treatment systems to add capacity or redundancy to centralized systems**—Smaller decentralized wastewater treatment technologies placed closer to the points of need can help reduce installation costs, operating costs, and energy requirements, and can enable gradual implementation as a useful alternative to building large-scale, centralized wastewater treatment plants. They may also benefit centralized systems by increasing capacity or system redundancy.[27] | | ■ | ■ | ■ | |
| **2.4.3. Demonstrate scalable water reuse approaches in small and under-resourced communities to address key implementation barriers**—Certain water treatment and reuse methods can require high installation costs or expensive on-going contracts that make their adoption challenging for small and under-resourced communities. Regional demonstrations of these technologies in smaller communities are needed to address the most common barriers to adoption related to affordability, operations, and maintenance. Modern water treatment and reuse technologies that are low-cost and scalable for meeting unique location-specific requirements can broadly increase the participation of smaller-scale communities in the future circular water economy. | | | | ■ | |

**Opportunity Area 2.5: Collaborative circular water economy model demonstrations**—Support multi-stakeholder or regional partnership opportunities to demonstrate the adoption pathways and potential benefits for transitioning toward sustainable and circular economy water management practices.

| Opportunities | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
|---|---|---|---|---|---|
| **2.5.1. Design a closed-loop system for wastewater treatment, energy and nutrient recovery, and carbon capture**—Design a prototype for a closed-loop system that supports sustainability and water circularity practices in agriculture including water reuse or recirculation, biodigesters[28] and solids management technologies, energy recovery, nutrient recovery[29], and carbon capture. Case studies could help quantify benefits including decreased infrastructure costs, improved manure management practices, new revenue streams, and higher profit margins.[30] | | ■ | ■ | | |

| Opportunity Area 2.5: **Collaborative circular water economy model demonstrations**—Support multi-stakeholder or regional partnership opportunities to demonstrate the adoption pathways and potential benefits for transitioning toward sustainable and circular economy water management practices. | | | | | |
|---|---|---|---|---|---|
| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **2.5.2. Build public-private relationships to demonstrate successful regional-level circular water economy pathways**—Evaluate regional opportunities to demonstrate circular water reuse projects at scale through public-private partnerships. Conduct a technoeconomic analysis that examines environmental and socioeconomic impacts of regional-level circular water economy models and provide strategies for adoption and scale-up. | | | ■ | ■ | |

# 3. Systems for Underserved Communities

Systems for collecting, treating, and reusing water resources can play a significant role in providing access to safe and readily available water for small, geographically dispersed, or under-resourced communities.[31] These communities, which are too small to benefit from the economics of scale in large centralized systems, have struggled with a range of issues including underrepresentation, distrust in utilities and government agencies, aging water infrastructure, water rights infringement, and economic and social inequalities. Enabling climate resilience and sustainable water management for communities with small-scale systems will require economic assistance and access to water reuse funding mechanisms, social and environmental advocacy support, and affordable "plug-and-play" technology options with reduced implementation risk and low energy requirements.

Water systems generally apply to the following three types of communities[32]:

1. **Dense Urban Areas**—Communities struggling with affordability and access near piped water supply in dense urban areas
2. **Small Centralized Systems**—Small communities with aging and non-compliant small centralized systems (i.e., serving 10,000 people or fewer; often fewer than 500 people)
3. **Wells and Individual Septic Systems**—Communities too geographically dispersed to have feasible centralized systems, reliant entirely on unregulated individual wells and individual septic systems

## Problem Statements

During the breakout group discussions of specific R&D needs, workshop participants provided additional information regarding specific challenges and issues regarding specific R&D needs for underserved communities and some potential proposed solutions.

### *Many utility investments are failing to maintain the pace of aging water infrastructure.*

Old or aging water infrastructure can be a direct threat to water quality and public health. Once water infrastructure fails, relief efforts typically focus on minimizing the impact of the failure rather than addressing the root cause. Infrastructural upgrades usually require higher utility rates which can disproportionately affect low-income users. Identifying leaks and developing modular circular systems can help to improve the infrastructure and disproportionately aid the most underserved communities.

### *Urban areas face a broad range of different water and wastewater inequities; the associated drivers are not well understood.*

There are hundreds of different municipalities whose needs vary as a function of water scarcity, water quality, water affordability, and infrastructure conditions. More research is needed to pursue high-impact opportunities and shared solutions for the most common drivers of water and wastewater inequity.

***Construction, operation, and maintenance costs of new and existing water and wastewater systems are unsustainably high.***

Many small communities struggle to generate enough revenue to meet the high capital cost requirements to install small-scale systems—especially as regulations become more stringent. Water and wastewater treatment and reuse projects are often too large or too difficult to maintain, leaving low-income households and small-scale communities with serious long-term economic disadvantages. Some communities are unable afford or receive adequate workforce support to maintain and operate their systems, while others have expressed an unwillingness to adopt new or non-standard systems because they believe that their potential underdevelopment poses a high risk of failure including irreversible consequences.

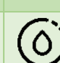
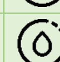
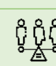
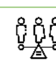
***Many communities distrust the abilities of utilities and government agencies to identify problems and implement solutions which hinders necessary stakeholder engagement.***

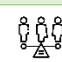
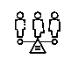
Historical inequities, unsuccessful past programs, and other causes of distrust have precluded some communities from working in collaboration with utilities and government agencies to achieve key objectives in sustainable water management, circular water reuse, and resilient infrastructure (see **Appendix D. Systems for Underserved Communities: Additional Stakeholders**).

## Opportunities

The following table organizes related ideas presented above by Key Opportunity Area, specific Opportunities, and overlapping Thematic Areas (represented by icons).

*Table 7: Systems for Underserved Communities' prioritized Opportunities with other overlapping Thematic Areas.*

| Key Opportunity Areas | Opportunities | Thematic Area | | | | |
|---|---|---|---|---|---|---|
| | | MUNICIPAL SYSTEMS | AGRICULTURAL SYSTEMS | SYSTEMS FOR UNDERSERVED COMMUNITIES | AI, DATA ANALYTICS & SENSORS | RESILIENCY & CIRCULAR ECONOMY |
| 3.1 Impact analyses and benefits assessments | Develop data-driven methods for studying common small-scale system needs |  | |  | |  |
| | Demonstrate the co-benefits of regionalized small-scale systems |  | |  | |  |
| | Assess low-cost, low energy intensity alternative water sources | | |  | | |
| 3.2 Workforce support and training initiatives | Expand opportunities in credentialing and experiential learning to strengthen the workforce pipeline | | |  | | |
| | Provide external engineering services to support technology implementation and maintenance | | |  | | |
| 3.3 Advocacy and community | Develop an impact modeling tool to enable participation in community-based modeling of water and wastewater treatment scenarios | | |  | | |

| Key Opportunity Areas | Opportunities | Thematic Area | | | | |
|---|---|---|---|---|---|---|
| | | MUNICIPAL SYSTEMS | AGRICULTURAL SYSTEMS | SYSTEMS FOR UNDERSERVED COMMUNITIES | AI, DATA ANALYTICS & SENSORS | RESILIENCY & CIRCULAR ECONOMY |
| **mobilization support** | Launch projects to co-develop community-centric solutions | | |  | | |
| | Develop and deploy strategies for water quality monitoring and other data-driven response measures | | |  | |  |
| | Foster partnerships with local NGOs to empower underserved communities (see **Appendix D. Systems for Underserved Communities: Additional Stakeholders**) | | |  | | |
| | Redesign assistance programs to facilitate long-term infrastructure upgrades with lower economic burden on lower-income households | | |  | | |
| **3.4 Design of low-cost point-of-use water treatment technologies** | Develop low energy intensity solutions for nutrient and pathogen removal | |  |  | |  |
| | Develop packaged modular systems for water treatment and reuse | |  |  | |  |

The following section provides detailed information on the Systems for Underserved Communities' Opportunity Areas and their associated Opportunities mapped out in color by different activity Opportunity Types. Each specific opportunity lists the applicable communities (**[1]** Dense Urban Areas; **[2]** Small Centralized Systems; **[3]** Wells and Individual Septic Systems).[33]

*Table 8: Systems for Underserved Communities' Opportunity Areas and Opportunities color-coded by Opportunity Type.*

| Opportunity Area 3.1: Impact analyses and benefits assessments—Develop a framework to characterize small-scale water and wastewater treatment systems and define the co-benefits of regionalized solutions. | | | | | |
|---|---|---|---|---|---|
| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **3.1.1. Develop data-driven methods for studying common small-scale system needs**—Categorization of water and wastewater treatment systems would provide researchers and decision-makers with a standardized framework for characterizing locality-based water and wastewater treatment needs and a fundamental understanding of the existing landscape of small-scale systems. These findings would help reveal opportunities for deploying shared solutions that address the intersection of common issues such as water scarcity, water quality, affordability, and infrastructure conditions.<br>*Applicable groups:*<br>*[1] Dense Urban Areas*<br>*[2] Small Centralized Systems*<br>*[3] Wells and Individual Septic Systems* | | | ■ | | |
| **3.1.2. Demonstrate the co-benefits of regionalized small-scale systems**—Combining small-scale water reclamation and reuse systems[34] through regional consolidation[35] can generate efficiency gains and promote cost-savings while maintaining state and local regulatory compliance. These projects could deliver co-benefits related to improved health, employment, energy security, reduction of fossil fuels, and environmental quality. Demonstrating regionalized small-scale systems and defining their co-benefits could help encourage community members to actively participate in the development and implementation of solutions for small-scale systems while supporting technology adoption for utility companies and decision-makers.<br>*Applicable groups:*<br>*[1] Dense Urban Areas*<br>*[2] Small Centralized Systems* | | | | ■ | |
| **3.1.3. Assess low-cost, low energy intensity alternative water sources**—Some smaller communities could potentially minimize their water usage and cost of water by embracing alternative water sources with lower energy intensity requirements. For example, a lifecycle analysis of decentralized rainwater harvesting systems[36] could quantify the cost and water efficiency benefits of disinfecting and purifying rainwater for potable water use.<br>*Applicable groups:*<br>*[1] Dense Urban Areas*<br>*[2] Small Centralized Systems*<br>*[3] Wells and Individual Septic Systems* | | | ■ | | |

| Opportunity Area 3.2: **Workforce support and training initiatives**—Enable a robust talent pipeline by providing workforce training programs and technology implementation support services that help small-scale communities incorporate climate resilience and circular water reuse into their unique water management practices. | | | | | |
|---|---|---|---|---|---|
| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **3.2.1. Expand opportunities in credentialing and experiential learning to strengthen the workforce pipeline**—Improve the talent pipeline by offering more workforce training and upskilling opportunities to ensure there are enough qualified professionals available to install, operate, and maintain new water and wastewater treatment system designs.<br>*Applicable groups:*<br>*[1] Dense Urban Areas*<br>*[2] Small Centralized Systems* | | | | | |
| **3.2.2. Provide external engineering services to support technology implementation and maintenance**—Many low-income households and small-scale communities are sold projects that are too large, too difficult to maintain, or inappropriate for their soil types, and are left with unsustainable financial burdens. Further, they often struggle to receive sufficient engineering support[37] on new water and wastewater technologies. A workforce development program[38] that provides regional training opportunities to individuals in close geographical proximity to water treatment systems and facilities could potentially address this issue.<br>*Applicable groups:*<br>*[1] Dense Urban Areas*<br>*[2] Small Centralized Systems* | | | | | |

**Opportunity Area 3.3: Advocacy and community mobilization support**—Foster programs and initiatives that increase small-scale community involvement in the co-development or implementation of resilient and affordable water and wastewater systems and empower these communities to leverage infrastructure investment opportunities.

| Opportunities | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
|---|---|---|---|---|---|
| **3.3.1. Develop an impact modeling tool to enable participation in community-based modeling of water and wastewater treatment scenarios**—To maximize the value and successful administration of state revolving funds (SRF)[39] for water and wastewater infrastructure upgrades, industry stakeholders and experts should engage directly with small communities to conduct impact modeling of various water and wastewater treatment scenarios. These collaborative engagements would help communities invest in water and wastewater systems that are resilient and affordable while building trust with government agencies and utility companies.<br>*Applicable groups:*<br>*[2] Small Centralized Systems* | | ■ | | ■ | |
| **3.3.2. Launch projects to co-develop community-centric solutions**—Leaders and community members should be involved in the co-development of water services and infrastructure solutions to achieve their specific needs and core values.[40] Co-development solutions should ensure a community-centric focus rather than merely adapting template solutions from nation-centric models. These collaborative efforts can deliver long-term economic and environmental gains while addressing key social justice elements.<br>*Applicable groups:*<br>*[1] Dense Urban Areas*<br>*[2] Small Centralized Systems* | | | | ■ | |
| **3.3.3. Develop and deploy strategies for water quality monitoring and other data-driven response measures**—Measurable data such as water quality, affordability, and access can be a powerful tool for driving decision support and strengthening advocacy messages to solve critical issues such as aging water infrastructure.[41] All communities could significantly benefit from having basic, uncomplicated access to data gathered through rigorous and transparent water quality monitoring programs.<br>*Applicable groups:*<br>*[1] Dense Urban Areas*<br>*[2] Small Centralized Systems*<br>*[3] Wells and Individual Septic Systems* | | ■ | ■ | | |
| **3.3.4. Foster partnerships with local NGOs to empower underserved communities**—Increase engagement with local non-government organizations (NGOs) whose mission is to advocate on behalf of low-income households and utility users to address locality-specific challenges.<br>*Applicable groups:*<br>*[1] Dense Urban Areas*<br>*[2] Small Centralized Systems*<br>*[3] Wells and Individual Septic Systems* | | | | ■ | |

| Opportunity Area 3.3: **Advocacy and community mobilization support**—Foster programs and initiatives that increase small-scale community involvement in the co-development or implementation of resilient and affordable water and wastewater systems and empower these communities to leverage infrastructure investment opportunities. | | | | | |
|---|---|---|---|---|---|
| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **3.3.5. Redesign assistance programs to facilitate long-term infrastructure upgrades with lower economic burden on lower-income households**—Increasing utility rates is essential for funding infrastructure upgrades, but it can disproportionately affect low-income households and utility customers. Well-designed assistance programs[42,43] could offer a sustainable, long-term solution that broadens access to affordable utility resources, prevents the shifting of financial burden to utility customers, and facilitates the allocation of funding for critical upgrades to water and wastewater systems.<br>*Applicable groups:*<br>*[1] Dense Urban Areas*<br>*[2] Small Centralized Systems* | | | | | |

| Opportunity Area 3.4: **Design of low-cost point-of-use water treatment technologies**—Design and develop point-of-use water treatment technologies that are user-friendly, low-maintenance, lower-cost throughout the full lifecycle, and more accessible to smaller communities. | | | | | |
|---|---|---|---|---|---|
| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **3.4.1. Develop low energy intensity solutions for nutrient and pathogen removal**—Newer nutrient removal technologies can deliver environmental and health benefits but tend to require high upfront investment costs. Research and development efforts should focus on developing affordable, low energy intensity[44] solutions for the remediation of groundwater nitrates and pathogens in smaller communities.[45]<br>*Applicable groups:*<br>*[2] Small Centralized Systems*<br>*[3] Wells and Individual Septic Systems* | | | | | |

**Opportunity Area 3.4: Design of low-cost point-of-use water treatment technologies**—Design and develop point-of-use water treatment technologies that are user-friendly, low-maintenance, lower-cost throughout the full lifecycle, and more accessible to smaller communities.

| Opportunities | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
|---|---|---|---|---|---|
| **3.4.2. Develop packaged modular systems for water reuse and resource recovery**—Research and development efforts should focus on designing and deploying modularized (or "plug-and-play") potable water reuse and filtration systems[46] that are primarily oriented toward the recovery of resources for secondary applications or markets. Standardizing packaged water treatment and reuse technologies that are easy to use and have lower maintenance requirements may also reduce the burden on workforce training as well as issues pertaining to troubleshooting and maintenance.<br>*Applicable groups:*<br>*[1] Dense Urban Areas*<br>*[2] Small Centralized Systems*<br>*[3] Wells and Individual Septic Systems* | | ■ | | | |

# 4. Artificial Intelligence, Data Analytics, and Sensors

Data science and analytics, in conjunction with sensors and AI-based techniques, have been used across many industry sectors to provide useful insights and quantitative intelligence that empowers organizations to make informed decisions and determine future courses of action. These technologies can similarly play a role in water sectors by helping stakeholders to optimize process control decisions for efficient water use and wastewater treatment, forecast extreme weather events that threaten water infrastructure, evaluate the health of water distribution and wastewater collection systems, and inform scenario planning for resilient infrastructure and sustainable water management. Some wastewater stakeholders are hesitant to adopt new Industry 4.0 technologies.

Compared with other sectors, many wastewater sector stakeholders (e.g., utilities and utility operators) have refrained from adopting data-driven analytical tools and automation due to high capital and operating costs, lack of skilled/trained operators, cybersecurity concerns, or unwillingness to overcome the learning curve required to implement a new system.

**What is Industry 4.0?**

Industry 4.0 represents the fourth industrial revolution in which manufacturing environments and other industrial sectors are transformed by the convergence of several key digital industry technologies such as robotics, cloud computing, artificial intelligence, sensor networks, analytics, and data to produce actionable intelligence and augment decision-making processes.

## Problem Statements

During the breakout group discussions of specific R&D needs, workshop participants referred to the following challenges and barriers to the adoption of sensor technologies and data-driven techniques for artificial intelligence & machine learning and some potential proposed solutions.

***Utility operators lack education and training in working with 4.0 technologies which leads to suspicion in adoption, especially for utilities supporting more remote or smaller municipalities; stakeholders need assurance in measurement accuracy and data integrity.***

Many smaller-scale communities do not know how to use or apply sensor technologies or predictive analytics for decision-making or may lack the ability to accommodate data analytics infrastructure requirements for their specific water treatment needs. Sensors also generate enormous volumes of data which can overwhelm operators who are unfamiliar with contemporary sensing techniques and data analytics. Operators need greater confidence that their sensor technologies are truly providing accurate measurement data, or whether they are failing, drifting, or subject to fouling. The underlying datasets of AI/ML predictions must be trustworthy and dependable.

***Sensor technologies are expensive, difficult to install, and difficult to implement and utilize.***

Sensors—especially those deployed in wastewater systems—are expensive, require considerable care and handling, are unsuitable for permanent installation, and are highly susceptible to harsh environments that cause fouling or inhibit the reliability of measurements. Remote sensors such as those deployed in remote agricultural areas have significant issues with long-term power supply and wireless connectivity.

***Existing data streams and sensors are underutilized.***

Some water treatment facilities are equipped with many sensors for complex and multi-parameter operations, such as facilities that recycle activated sludge for resource recovery. These data streams could feed AI/ML tools for water quality optimization, but they are underutilized or poorly integrated with digital twins and other predictive modeling tools. Understanding underlying reasons for lack of utilization is important for increased implementation.

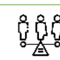
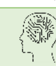
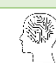
***Many AI/ML products lack interoperability.***

While several AI/ML products are available on the market, many are considered "one-off" options, and there are no easy methods or systems-level approaches for integrating these products into a single workstream.

## Opportunities

The following table organizes related ideas presented above by Key Opportunity Area, specific Opportunities, and overlapping Thematic Areas (represented by icons).

*Table 9: **Artificial Intelligence, Data Analytics, and Sensors'** prioritized Opportunities with other overlapping Thematic Areas.*

| Key Opportunity Areas | Opportunities | Thematic Areas | | | | |
|---|---|---|---|---|---|---|
| | | MUNICIPAL SYSTEMS | AGRICULTURAL SYSTEMS | SYSTEMS FOR UNDERSERVED COMMUNITIES | AI, DATA ANALYTICS & SENSORS | RESILIENCY & CIRCULAR ECONOMY |
| **4.1 Data-driven modeling solutions for water facility management and process control** | Develop scalable optimization methods via open-source software solutions for process control | | | |  | |
| | Develop a tool for accessing and analyzing online-based water and wastewater treatment sensor data |  | |  |  | |
| **4.2 Distributed sensors for early detection and response** | Create new data streams with existing sensor technologies | | | |  | |
| | Develop remote sensors for detecting leaks and contaminants of emerging concern |  | |  |  |  |
| **4.3 Methods to improve sensor reliability and data accuracy** | Apply analytics to improve sensor measurement confidence and reliability | | | |  | |
| | Design robust physical sensors for measuring physical properties in wastewater systems | | | |  | |
| **4.4 AI/ML-ready data architectures to support decision-making** | Establish secure data sharing formats and platforms to make data useful for AI/ML | | | |  | |
| | Leverage existing plant operational data for plant optimization | | | |  | |
| | Apply non-traditional public datasets to water quality predictions | | | |  | |
| | Increase interpretability and trust in sensor data for decision-making | | | |  | |

The following section provides detailed information on the Artificial Intelligence, Data Analytics, and Sensors breakout sessions' Opportunity Areas and their associated Opportunities mapped out in color by activity Opportunity Types.

*Table 10: **Artificial Intelligence, Data Analytics, and Sensors**' Opportunity Areas and Opportunities color-coded by Opportunity Type.*

**Opportunity Area 4.1: Data-driven modeling solutions for water facility management and process control**—Enable data-driven modeling solutions to support water treatment facilities with the ability to predict system performance, test new strategies, and inform decision-making.

| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
|---|---|---|---|---|---|
| **4.1.1. Develop scalable optimization methods via open-source software solutions for process control**—Open-source software solutions are needed for integrating real-time sensor data to optimize process control decisions for energy use and meeting specific effluent quality objectives. To maximize usefulness, these software suites must optimize control decisions that minimize or maximize multiple competing objective functions that are subject to water system constraints. | | | | | |
| **4.1.2. Develop a tool for accessing and analyzing online-based water and wastewater treatment sensor data** —Small-scale facilities would benefit from assistance with the implementation of digital platforms and computing solutions (e.g., central, cloud-based, edge-based) to leverage robust data analytics for assessing water quality without the need for substantial or expensive localized infrastructure upgrades. These digital platforms could provide facilities with access to massive datasets[47] from across different scales of the utility infrastructure for local decision-making purposes. Cloud-based data analytics, for example, could be useful for processing images of water flow (e.g., hyperspectral) to elucidate water quality. | | | | | |

**Opportunity Area 4.2: Distributed sensors for early detection and response**—Deploy sensor networks for early detection of and response to issues related to water quality, system health, extreme events, and other key data streams.

| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
|---|---|---|---|---|---|
| **4.2.1. Create new data streams with existing sensor technologies**—Instead of developing new sensors, efforts focus on engaging facility managers and owners to facilitate the creation of new low-cost and low-maintenance data streams through the application of existing sensor technologies. These new data streams could offer insights on real-time water quality, system health, and other useful indicators. For example, these sensors could be used for non-contact applications that measure vibrations, sound, and reflected light from water surfaces. | | | | | |

| **Opportunity Area 4.2: Distributed sensors for early detection and response**—Deploy sensor networks for early detection of and response to issues related to water quality, system health, extreme events, and other key data streams. | | | | | |
|---|---|---|---|---|---|
| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **4.2.2. Develop remote sensors for detecting leaks and contaminants of emerging concern**[48]—Low-cost remote sensors deployed across water distribution and wastewater collection networks would help utility companies prioritize maintenance activities and respond quickly based on various physical, chemical, and biological parameters for measuring water quality and system health.[49] | | ■ | | | |

| **Opportunity Area 4.3: Methods to improve sensor reliability and data accuracy**—Employ techniques that seek to improve sensor measurement confidence, reduce uncertainties, and overcome sensitivity issues with physical sensor applications. | | | | | |
|---|---|---|---|---|---|
| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **4.3.1. Apply and enhance analytics to improve sensor measurement confidence and reliability**—Utility companies and water treatment professionals would benefit from real-time predictive data analytics that could provide information regarding the confidence level of sensor readings including specific factors such as drift, fouling, and actual anomalies. Since subtle changes in water quality can challenge the accuracy of physical sensors, low-cost software sensor computer models—or "soft sensors"—are a useful way to estimate water quality using various physical parameters like flow, pressure, and specific chemical measurements. | | ■ | | | |
| **4.3.2. Design robust physical sensors for measuring physical properties in wastewater systems**—The materials used for most existing sensor technologies are unable to withstand the conditions of wastewater streams for extended periods of time. Robust physical sensors—especially those in locations that are difficult to access—are needed to measure the physical state of wastewater systems and biosolid-related samples including flow levels, sludge health, and settleability. | | ■ | | | |

**Opportunity Area 4.4: AI/ML-ready data architectures to support decision-making**—Create data architectures that enable the use of AI/ML tools for data-driven decision-making

| Opportunities | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
|---|---|---|---|---|---|
| **4.4.1. Establish secure data sharing formats and platforms to make data useful for AI/ML**[50]—Water and wastewater facilities would benefit from a central repository for water supply and consumption data to enable the use of AI/ML tools for leak detection, flood control, floodwater management, pandemic response, and other key aspects related to water quality. Standardized data sharing platforms would help support the integration of IT and OT aspects of water and wastewater treatment facilities. Under-resourced or underrepresented utilities could further benefit from access to curated benchmark datasets for decision-making and plant optimization. Encouraging the use of cloud-based business intelligence tools among management professionals, for example, could help provide a steppingstone for using AI/ML predictive analysis in other aspects of wastewater treatment.[51] | | ■ | | | |
| **4.4.2. Leverage existing plant operational data for plant optimization**—Several utility companies and providers have already generated vast volumes of operational data. This data could be securely aggregated and used in data-driven modeling tools for performance prediction and optimization. This opportunity should seek to clarify what types of operational data are available and useful for ML-based optimization including the key parameters of interest for optimization treatment plant operations. | | | ■ | ■ | |
| **4.4.3. Apply non-traditional public datasets to water quality predictions**—Other industry sectors have successfully used AI/ML tools to discern trends in non-traditional datasets and apply them for performance prediction and optimization purposes. For example, some technicians in the water and wastewater sectors are examining the potential for using AI/ML to make future water quality predictions based on weather data. Interagency partnerships with entities[52] that monitor national weather information could help facilitate the sharing of non-traditional datasets to enable these predictive capabilities. | | | | ■ | |
| **4.4.4. Increase interpretability and trust in sensor data for decision-making**—Incorporating psychological and design-based thinking research into real-time analytics and improving the user friendliness of human-computing interfaces would make it easier for water treatment operators to make informed decisions in water treatment optimization based on sensor data. | | ■ | | ■ | |

# 5. Resilience and Circular Economy

The effects of climate change on water demand and usage and the need for sustainable water management principles is prompting utilities and other decision-makers across the water and wastewater sector to incorporate infrastructural resilience and circular economy into their long-term strategies and resource plans. Opportunities to achieve these objectives include but are not limited to robust data analytics to quantify uncertainties and predict future scenarios, novel economic models and technologies for water reuse and resource recovery, and user-friendly decision support tools to guide decision-making for sustainable water use and adaptive climate change measures.

## Problem Statements

During the breakout group discussions of specific R&D needs, workshop participants referred to the following challenges and barriers to resiliency & circular economy and some potential proposed solutions.

***Variable and temporally heterogenous flow rates from alternative sources present concern for water distribution and wastewater collection systems, as well as the resulting water quality.***

Since water distribution and wastewater collection systems are designed for consistently higher flow rates, transitioning to circular water economy models for increased water re-use and system efficiency could cause major infrastructural problems such as degradation of chlorine residuals in standing water or corrosive gases generated by slower-moving sewage. These impacts on the design of distribution and collection systems are not well understood.

***Climate change is accelerating the growth of harmful algal blooms (HABs) which threaten source water quality.***

Nutrient run-off, higher carbon dioxide levels in the water and air, and warmer average water temperatures is causing a higher occurrence of toxic HABs in source waters, plant effluents, and wastewater treatment intakes.

***With about 40% of the US population living in coastal regions,[53] rising sea levels and increases in extreme flooding events can overwhelm water and wastewater systems and critical infrastructure components.***

Flooding can overwhelm water and wastewater systems, compromise critical infrastructure components, and potentially cause significant indirect disruptions to surrounding areas. Hydrological forecasting models could help communities identify the time and/or location of high-risk areas to prioritize investments in protective measures and other climate change adaptation strategies.

***Climate change events will increasingly challenge the water availability, reliability, and resilience with some areas having too much water and others too little water; the***

***uncertainty of model outputs is challenging for non-technical experts to manage and interpret.***

Despite large volumes of data to feed simulations, climate models have inherent uncertainties that limit the ability to make statistically robust predictions regarding extreme weather events. Model outputs and uncertainties are generally more difficult for users and decision-makers to manage or interpret as opposed to model developers.

***The current design standard for engineering projects is the 100-year flood event, which has become outdated because these flood events now occur with climate change more frequently than every hundred years, suggesting a need for new initiatives in design criteria.***

Utilities are reluctant to allocate resources for long-term engineering projects[54]—especially for climate adaptation—without a strong understanding of the risk and uncertainty associated with potential future scenarios. Engineering design standards based on climate risks could help utilities and community decision-makers justify the costs associated with climate adaptation and infrastructure resilience.

## Opportunities

The following table organizes related ideas presented above by Key Opportunity Area, specific Opportunities, and overlapping Thematic Areas (represented by icons).

*Table 11: **Resilience and Circular Economy**'s prioritized Opportunities with other overlapping Thematic Areas.*

| Key Opportunity Areas | Opportunities | Thematic Areas | | | | |
|---|---|---|---|---|---|---|
| | | MUNICIPAL SYSTEMS | AGRICULTURAL SYSTEMS | SYSTEMS FOR UNDERSERVED COMMUNITIES | AI, DATA SYSTEMS & SENSORS | RESILIENCY & CIRCULAR ECONOMY |
| 5.1. Robust AI capabilities for extreme event interpretation and prediction | Incorporate uncertainty into extreme event scenario planning tools | | | | ✓ | ✓ |
| | Research the indicators for predicting and mitigating harmful algal blooms | | ✓ | | ✓ | ✓ |
| | Determine hydrological forecasting indicators for sea level rise and inland flooding | | | | ✓ | ✓ |
| 5.2. Locality-specific decision-making tools and infrastructure adaptation planning | Translate large-scale climate modeling results into decision-making tools and infrastructure adaptation planning for local communities | ✓ | | ✓ | ✓ | ✓ |
| | Characterize locality-specific conditions to inform adaptive climate measures | | | | ✓ | ✓ |
| | Develop open-source software tools for making localized climate projections associated with water | ✓ | | ✓ | ✓ | ✓ |
| | Design water distribution and collection systems that are resilient to changing flow rates | ✓ | ✓ | ✓ | | ✓ |
| | Research the effectiveness of nature-based options for urban climate adaptation planning | | | | | ✓ |
| | Study the climate adaptation needs for other critical infrastructure | ✓ | ✓ | ✓ | ✓ | ✓ |
| 5.3. Cross-sector water monitoring framework for informed decision-making | Create a transparent data tracker for regional water movement | | | | ✓ | ✓ |
| | Launch cross-sector impact analysis projects to characterize cost and sustainability data | | | | | ✓ |
| | Develop a real-time water quality monitoring capability to inform reuse applications | ✓ | ✓ | | ✓ | ✓ |
| 5.4. Macroeconomic impact studies of circular economy transitions | Align water circularity metrics with climate change adaptation goals | | | | | ✓ |
| | Create a publicly available emissions analysis tool | | | | ✓ | ✓ |
| 5.5. Maximizing the value of water reuse and resource recovery | Identify resource recovery market opportunities | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Quantify the shared benefits of co-located water reuse scenarios | | | | | ✓ |

The following section provides detailed information on the Resilience and Circular Economy breakout sessions' Opportunity Areas and their associated Opportunities mapped out in color by different activity Opportunity Types.

*Table 12: **Resilience and Circular Economy**'s Opportunity Areas and Opportunities color-coded by Opportunity Type.*

| <u>Opportunity Area 5.1</u>: **Robust AI capabilities for extreme event interpretation and prediction**—Develop robust and trustworthy AI techniques to recognize patterns in extreme weather indicators and accurately predict high-impact weather events | | | | | |
|---|---|---|---|---|---|
| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **5.1.1. Incorporate uncertainty into extreme event scenario planning tools**—Utilities would benefit from decision-making tools and other scenario planning methods that account for different types of uncertainty variables when making decisions about long-term adaptive climate measures based on plausible extreme weather event futures. | | ■ | ■ | | |
| **5.1.2. Research the indicators for predicting harmful algal blooms**—As climate change drives the degradation of source water quality, AI-driven analytics can help communities identify and predict the indicators of harmful algal bloom (HAB) growth. | ■ | | | | |
| **5.1.3. Determine hydrological forecasting indicators for sea level rise and inland flooding**—To prioritize investments for climate mitigation, decision-makers need robust analytical tools to accurately predict the time and location of extreme weather events that lead to inland flooding and sea level increases. | ■ | ■ | ■ | | |

| <u>Opportunity Area 5.2</u>: **Locality-specific decision-making tools and infrastructure adaptation planning**—Develop locality-specific decision-making tools and explore infrastructure adaptation measures to account for climate change and circular economy models | | | | | |
|---|---|---|---|---|---|
| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **5.2.1. Translate large-scale climate modeling results into decision-making tools and infrastructure adaptation planning for local communities**—Advanced climate prediction models developed by key government agencies[55] and their laboratory affiliates could be translated into decision support tools for community decision-makers to use in climate change scenario planning and mitigation. | | | ■ | | |
| **5.2.2. Characterize locality-specific conditions to inform adaptive climate measures**—Implementing adaptive climate change measures requires an understanding of the cost to adapt versus the economic consequences of inaction. These costs are informed by locality-specific characteristics such as distribution size, population density, and permeable area. Characterizing locality-specific conditions would help communities assess their specific regional needs and provide economic justification needed to confidently apply adaptive climate change measures. | | | ■ | | |

**Opportunity Area 5.2: Locality-specific decision-making tools and infrastructure adaptation planning**—Develop locality-specific decision-making tools and explore infrastructure adaptation measures to account for climate change and circular economy models

| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
|---|---|---|---|---|---|
| **5.2.3. Develop open-source software tools for making localized climate projections associated with water**—Open-source software suites are an accessible and affordable option that utilities and engineering firms could use to account for locality-specific conditions when making projections and decisions about the associated impacts of climate change. | | ■ | | ■ | |
| **5.2.4. Design water distribution and collection systems that are resilient to changing flow rates**—Distribution and collection systems, which are designed to handle large volumes of water and wastewater, may be negatively impacted by lower flow rates due to more on-site re-use and treatment.[56] Conversely, some systems may benefit from designs that are more resilient to high flooding conditions from extreme weather events. | | ■ | | ■ | |
| **5.2.5. Research the effectiveness of nature-based options for urban climate adaptation planning**—Many decision-makers have expressed the need for nature-based solutions (e.g., bank filtration, green roofs, engineered wetlands) as part of their overall climate change adaptation strategies. These options rely on the use of biodiversity and ecosystem-based approaches in urban water management and planning. Research efforts are needed to understand the cost and benefits of nature-based approaches for mitigating climate change impacts to encourage the future implementation of scalable climate adaptation strategies. | ■ | ■ | ■ | | |
| **5.2.6. Study the climate adaptation needs for other critical infrastructure**—Other critical infrastructure such as power generation, communications, transportation, and chemical production will also need to evolve and adapt to climate change to support the water and wastewater sector. | | | ■ | | |

**Opportunity Area 5.3: Cross-sector water monitoring framework for informed decision-making**—Develop a cross-sector data monitoring framework to track water quality, movement, and consumption data to inform decision-making for climate resilience and water reuse

| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
|---|---|---|---|---|---|
| **5.3.1. Create a transparent data tracker for regional water movement**—Using distributed sensor networks to securely monitor local water cycles, withdrawals, consumption, and other aspects of water movement would enable local policymakers to make more informed decisions about zoning, permitting, and investments related to adaption infrastructure to climate change future and circular water economy models. | | ■ | ■ | ■ | |

| Opportunity Area 5.3: Cross-sector water monitoring framework for informed decision-making—Develop a cross-sector data monitoring framework to track water quality, movement, and consumption data to inform decision-making for climate resilience and water reuse | | | | | |
|---|---|---|---|---|---|
| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **5.3.2. Launch cross-sector impact analysis projects to characterize cost and sustainability data**[57]—Assessing the broad consequences and economic impacts of future water reuse scenarios would require well-characterized cost and sustainability data across multiple industry sectors. An array of highly instrumented demonstration projects could generate the necessary energy and water use data for assessing these potential impacts. | | | | | |
| **5.3.3. Develop a real-time water quality monitoring capability to inform reuse applications**—To optimize circular water economy reuse across industry sectors, research and development efforts should aim to define minimum water quality inputs, develop decision trees for various water quality levels, and establish a real-time monitoring capability to track water quality. | | | | | |

| Opportunity Area 5.4: Macroeconomic impact studies of circular economy transitions—Examine the effects of transitioning to circular water economy models with respect to water quality, water footprint, infrastructure resilience, crop production choices, and unintended consequences | | | | | |
|---|---|---|---|---|---|
| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **5.4.1. Align water circularity metrics with climate change adaptation goals**—The broad water and wastewater community must conduct studies to determine if activities for transitioning toward circular water economy models are sufficiently addressing key metrics for climate change adaptation and mitigation including energy use, water sustainability, and greenhouse gas emissions reductions. | | | | | |
| **5.4.2. Create a publicly available emissions analysis tool**[58]—Water and wastewater sector stakeholders need a robust lifecycle analysis tool to assess progress toward climate change adaption measures and circular water economy goals and enable their participation in carbon markets and related funding programs. This lifecycle analysis tool would resemble Argonne National Laboratory's publicly available GREET model but would focus on water usage data for making rigorous and verifiable estimations of greenhouse gas emissions. | | | | | |

| **Opportunity Area 5.5: Maximizing the value of water reuse and resource recovery**—Encourage stakeholder collaboration to identify market opportunities for recovered wastewater products and determine useful applications for water reuse | | | | | |
|---|---|---|---|---|---|
| **Opportunities** | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **5.5.1. Identify resource recovery market opportunities**—Stakeholders across the water and wastewater community must create a holistic circular water economy strategy that simplifies the process of finding markets for components and product that can be recovered from industrial wastewater. This includes methods for testing different water reuse scenarios based on the quantity and availability of supplies across geographical regions. | | | X | | |
| **5.5.2. Quantify the shared benefits of water reuse scenarios**—multi-stakeholder analyses are needed to quantify the shared benefits of transitioning toward circular water economy models and encourage participation in future water reuse scenarios. These analyses should also examine water reuse scenarios that rely on integrated utility centers and systems such as the co-location of wastewater treatment, circular resource management, and energy generation. | | | X | | |

# Conclusion

The AMO Water and Wastewater RD&D Workshop Series sought to gather and synthesize the input from attendees across the various water use and end user sectors for three core goals: (1) to better understand challenges to achieve a modern, sustainable, resilient, and climate-adaptive water and wastewater treatment infrastructure; (2) advise RD&D and analysis needs; and (3) expand the stakeholder audience and funding opportunity reach. On Day 1, attendees heard not only from federal and national laboratory perspectives on energy-water opportunities, but also from thought leaders outside of the government sphere on their perceptions of needs within each Thematic Area. The Thematic Areas are described as municipal systems at all scales; agricultural water and wastewater systems; water systems for underserved communities; AI/ML, data, and sensors; and the crowd-sourced topic on resilience and the circular economy.

Participants articulated a broad range of needs, opportunities, and potential solutions that were broadly categorized (with much overlap) into Opportunity Types: early-stage research; applied R&D; assessments and problem analyses; stakeholder engagement; and policy development. Overarching interrelated opportunities, so-called "Idea Clusters," that emerged across all the breakout sessions included:

- Designing cost-effective water treatment, recovery, and reuse technologies (which was broadly categorized as a mainly applied R&D opportunity type, as well as having assessment aspects).
- Characterizing locality-based water and wastewater treatment needs (which was broadly categorized as mainly an assessment opportunity type with some applied R&D aspects).
- Developing community-level models and decision support tools (which was a relatively even mix of overlapping applied R&D, assessment, and stakeholder engagement opportunity types).
- Assessing lifecycle environmental impacts (which was largely an assessment opportunity type with aspects of applied R&D when considering the development of the analytical tools).
- Assessing resilience of infrastructure and water treatment facilities (which was largely an assessment opportunity type with aspects of early-stage research when considering hydrological forecasting indicators).
- Developing and demonstrating nature-based solutions (which is a relatively even mix of early-stage research, applied R&D, and assessment).

Table 13, below, illustrates these Idea Clusters of interrelated opportunities across all the five topical Thematic Areas that share common objectives or intended outcomes. It also shows which Thematic Areas and Opportunity Types that are most applicable to each specific opportunity. The Thematic Areas described in Table 13 correspond to Figure 1 from the main report, which is included here for clarity as Figure 2.

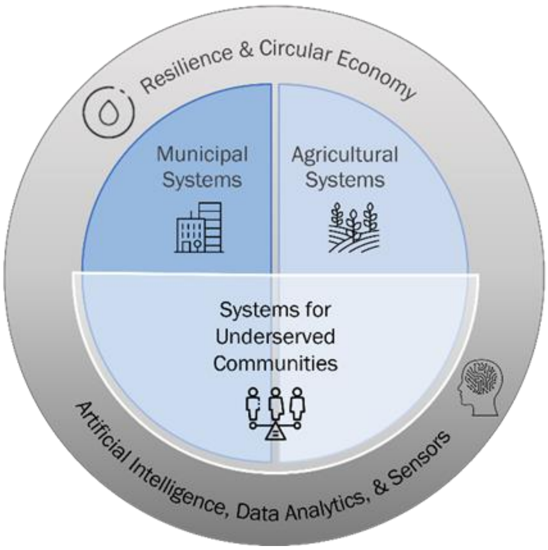



***Figure 2:*** *Schematic depicting relationship between the thematic area topic sessions*

***Table 13: Idea Clusters*** *of interrelated opportunities across the five topical Thematic Areas along with potential Opportunity Types in which they apply.*

| Idea Clusters | Opportunities | Thematic Area | Opportunity Type | | | | |
|---|---|---|---|---|---|---|---|
| | | | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **Design of cost-effective water treatment, recovery, and reuse technologies** | 2.4.1. Develop cost-effective approaches to achieve target mineral composition in recycled water |  | | ■ | | | |
| | 2.5.1. Design a closed-loop system for wastewater treatment, energy and nutrient recovery, and carbon capture |  | | ■ | ■ | | |
| | 1.4.2. Design and develop novel wastewater treatment solutions and water reuse opportunities for rising total dissolved solids (TDS) concentrations based on comprehensive environmental and economic assessments |  | | ■ | ■ | | |
| | 5.3.3. Develop a real-time water quality monitoring capability to inform reuse applications |  | | ■ | | | |

| Idea Clusters | Opportunities | Thematic Area | Opportunity Type | | | | |
|---|---|---|---|---|---|---|---|
| | | | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| Characterize locality-based water and wastewater treatment needs | 2.2.1. Develop data-driven methods for prioritizing locality-specific water management decisions | | | ■ | ■ | | |
| | 3.1.1. Develop data-driven methods for studying common small-scale system needs | | | | ■ | | |
| | 5.2.2. Characterize locality-specific approaches to inform adaptive climate measures | | | | ■ | | |
| Development of community-level models and decision support tools | 4.1.2. Develop a tool for accessing and analyzing online-based water and wastewater treatment sensor data | | | ■ | | | |
| | 4.4.3. Apply non-traditional public datasets to water quality predictions | | | | | ■ | |
| | 2.2.1. Develop data-driven methods for prioritizing locality-specific water management decisions | | | ■ | ■ | | |
| | 1.3.2. Design scalable and adaptable digital tools to enable modeling, visualization, and optimization of current full-scale treatment processes | | | ■ | ■ | ■ | |
| | 5.2.1. Translate large-scale climate modeling results into decision-making tools and infrastructure adaptation planning for local communities | | | | ■ | | |
| Assess lifecycle environmental impacts | 4.1.2. Develop a tool for accessing and analyzing online-based water and wastewater treatment sensor data | | | ■ | | | |
| | 2.1.3. Conduct lifecycle assessments on biosolids reuse applications | | | | ■ | | |
| | 1.1.1. Develop a lifecycle analysis tool to inform facility- and regional-level efficiency gains | | | | ■ | | |
| | 1.4.1. Conduct a comparative analysis of centralized and distributed water treatment systems | | | | ■ | | |
| | 5.4.2. Create a publicly available emissions analysis tool | | | | ■ | | |
| Assess resilience of infrastructure and water treatment facilities | 2.1.2. Evaluate the infrastructural and environmental implications of large-scale expansion of water reuse practices | | | | ■ | | |
| | 1.4.3. Analyze the resiliency needs of interconnected water-energy systems | | | | ■ | | |
| | 5.1.3. Determine hydrological forecasting indicators for sea level rise and inland flooding | | ■ | | ■ | | |
| Develop and demonstrate | 2.3.1. Conduct regional prototype demonstrations of nature-based solutions for reducing run-off and nutrient losses | | ■ | ■ | ■ | | |

| Idea Clusters | Opportunities | Thematic Area | Opportunity Type | | | | |
|---|---|---|---|---|---|---|---|
| | | | EARLY-STAGE RESEARCH | APPLIED R&D | ASSESSMENT | STAKEHOLDER ENGAGEMENT | POLICY |
| **nature-based solutions** | 5.2.5. Research the effectiveness of nature-based options for urban climate adaptation planning | | | | | | |

Some of these ideas reflect ongoing work funded through AMO, particularly in the NAWI Desalination Hub, the recent 2021 funding opportunity announcement and prize competition in Advanced Water Resource Recovery Systems R&D and analysis projects, and other connected AMO portfolios such as the Clean Energy Smart Manufacturing Institute (CESMII), which has been developing data-driven analytical tools and automation to tackle the Industry 4.0 future (see **Table 10**, Opportunity 4.4.1). Ongoing coordination with other offices and agencies such as through the DOE's Nexus of Energy and Water for Sustainability (NEWS) RD&D initiative, the Department of the Interior (DOI) U.S. Bureau of Reclamation's water treatment interagency working group (WATR), and EPA's Water Reuse Action Plan (WRAP) are other ways that the DOE is strengthening the effort to reach stakeholders more comprehensively.

In general, the workshop outcomes emphasized furthering cross-office and cross-agency collaborations. Attendees articulated the need for continued efforts in research, development, demonstration, and deployment as well as workforce development, stakeholder engagement and regulation. More focus on systems-level innovations at the regional and local (particularly community) scales as well as the inclusion of climate-resilient design and triple-bottom-line activities (social responsibility, economic prosperity, and environmental stewardship) continually emerged during the workshop.[59]

This report is consistent with the NAWI roadmaps (**Appendix C. Additional Resources**) and demonstrates continued support for AMO's current energy-water portfolio as well as suggests ideas for additional funding solicitations and interagency collaborations. It also indicates to other offices and agencies of opportunity areas where they may be able to contribute and where collaborations may be appropriate.

# Appendix A. Workshop Structure and Agenda

The AMO Water and Wastewater RD&D Workshop Series took place over three days: December 7, 14, and 16 via the virtual Zoom.gov platform.

## Day 1 (Dec. 7) – Setting the stage

Day 1 provided context and background of currently AMO-funded programs in the energy-water portfolio, featuring two core plenary panels:

- **DOE analysis**: The first plenary panel highlighted currently funded efforts from AMO's energy-water nexus portfolio. Moderated by Jordan Macknick of NREL, the four national laboratory panelists discussed past and present analysis, highlighting work from the National Alliance for Water Innovation (NAWI) —DOE's desalination hub—that has published multiple technology roadmaps representing different sectors and RD&D needs.
- **Non-government perspective**: The second plenary panel gathered experts from outside the government, representing folks in industry, utility, consultants, and non-profits. DOE's Mike Rinker moderated this session, queuing up both the similarities and differences in water and wastewater priorities for these thought leaders' organizations and posing challenging questions on how the federal government can better work with these institutions in implementing impactful RD&D.

Both plenary panels were followed by short Q&A periods to answer the audience's questions. At the end of Day 1, attendees were introduced to an interactive user-input platform called XLeap, in which they voted for a crowd-sourced topic to discuss during the last breakout session planned on Day 3. Day 1 was recorded so attendees could later access any information. The link to Day 1's recording can be found here: https://www.energy.gov/eere/amo/events/day-1-water-and-wastewater-rdd-series

## Day 2 (Dec. 14) and Day 3 (Dec. 16) – Breakouts

Day 2 and 3 solicited feedback from attendees through breakout rooms using XLeap. Day 2 featured topic-specific breakouts in data/artificial intelligence (AI)/machine learning (ML) and agricultural water and wastewater reuse systems. Day 3 featured topic-specific breakouts in municipal water systems at all scales, small-scale community water systems, and a crowd-sourced topic. The crowd-sourced topic voted upon by attendees on Day 1 was "**Translating climate change impacts on water systems infrastructure and informing a circular water economy.**" The beginning of each topical breakout session began with a 10-minute presentation by an AMO representative as well as a national laboratory or other agency co-led to lay the framework of the discussion. Attendees further divvied into mini-breakouts (of up to 20 people each) and worked on answering the following discussion questions both through the anonymous typed XLeap input as well as verbal engagement with others in their mini-breakout rooms:

| Breakout Rooms | Focus Questions |
|---|---|
| 1. Artificial Intelligence, Data Analytics, and Sensors | • Sensors are used for many aspects of water and water treatment. What are today's RD&D needs?<br>• Artificial intelligence and machine learning have significant roles in other sectors. How can RD&D enable water sectors to similarly benefit? |
| 2. Agricultural Systems | • What technologies or problems do you think have not been adequately explored by current research, development, demonstration, and deployment?<br>• What are some of the unintended consequences/long-term concerns of agricultural water reuse that we should avoid/address? |
| 3. Municipal Systems | • What challenges and needs in municipal water and wastewater could be addressed by analysis, research, development, or deployment funding? |
| 4. Small-Scale Systems | • What are the largest drivers of the water and wastewater inequities and challenges for each of these communities? (i.e., a. Communities struggling with affordability and access near piped water supply in dense urban areas; b. Small communities with aging and non-compliant small centralized systems [i.e., serving 10,000 people or fewer; often fewer than 500 people]; c. Communities too geographically dispersed to have feasible centralized systems; reliant entirely on unregulated individual wells and individual septic systems<br>• What are some opportunities or solutions to tackle both water delivery and wastewater treatment for each of these communities? |
| 5. Resilience and Circular Economy | • What RD&D is needed for next-generation models to forecast infrastructure challenges and adaptive measures to extreme events?<br>• What RD&D is needed to develop the circular water economy necessary to inform investments (industry, farmer, municipality)? |

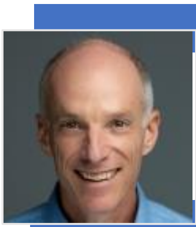
These breakout sessions were not recorded to facilitate an open environment to share candid thoughts and ideas.

# Day 1 Summaries

Melissa Klembara of DOE opened the workshop, outlining the objectives of the workshop and explaining the order of the day as well as the agenda for the rest of the workshop. Melissa described the current 20th century linear model of fresh water sources, centralized treatment, and outdated infrastructure, and need to redefine how it can be built back better, smarter, and wiser. She gave an overview of energy-water nexus activities within AMO with respect to its mission, as well as EERE priorities within DOE. Melissa then ended her keynote, broadening out the scope to current interagency collaborations and finally the call for attendees from all sectors to likewise participate in voicing the future vision of water.

### *DOE Analysis: National Laboratory Perspective*

Jordan Macknick of NREL then took to the virtual stage to moderate the panel of national laboratory speakers who conduct analysis across AMO's water space. As a lead of many analysis projects, Jordan introduces the DOE-funded analysis work of water systems from three different angles: desalination and reuse, wastewater technologies and technology resource recovery, and industrial manufacturing water reuse.



**DAVID SEDLAK**
NATIONAL ALLIANCE FOR WATER INNOVATION (NAWI)

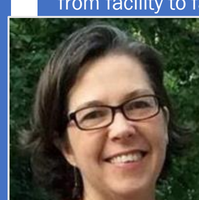
Prof. David Sedlak is the Plato Malozemoff Professor of Environmental Engineering at the University of California, Berkeley. He is also the Director of the Berkeley Water Center and serves as the Research Advisory Council Chair for NAWI.

David described NAWI as having a dual strategy: (1) technological innovations to drive down cost and improve performance, and (2) small-scale, distributed treatment to reduce water conveyance needs. He discussed NAWI's research roadmaps and the A-PRIME (autonomous, precise, resilient, intensified, modular, and electrified) research towards a circular economy.

David highlighted where NAWI fits on the US desalination R&D ecosystem, working on not only basic research, but technology development and pilots towards demonstrating higher TRL potential, looking for inspiration also in other industrial sectors.

**AJ SIMON**
LAWRENCE LIVERMORE NATIONAL LAB

A.J. Simon is the Group Leader for Energy and Associate Program Leader for Climate Resilient. A.J. described the complex unit operations for water and wastewater treatment technology, from biological to electrochemical methods; all which involve a plethora of supporting units like pumps and heat exchangers, and all of which vary from facility to facility.



**JENNIFER STOKES-DRAUT**
LAWRENCE BERKELEY NATIONAL LAB

Dr. Jennifer Stokes-Draut is an Energy/Environmental Policy Researcher in the Sustainable Energy & Environmental Systems Dept. Jenn discussed the facilities' energy/carbon implications and how the team can narrow down the most cost-effective approaches (e.g., non-traditional water) for GHG reduction.

**PRAKASH RAO**
LAWRENCE BEREKLEY NATIONAL LAB

Dr. Prakash Rao is an Energy/Environmental Policy Researcher in the Building & Industrial Applications Dept. Prakash started his talk outlining the manufacturing water flows from the supply to use to treatment and discharge. Risks to water supply are affected by drought, aridification, and deterioration of water quality due to climate change as well as human impact.

Prakash then made the case for the potential for water reuse, recognizing the need for understanding the various tradeoffs including the true valuation of water, contaminant concentrations and volumes for key subsectors/processes, economics compared to energy performance benchmarks and byproduct extraction.

Prakash's conclusion: while industrial reuse can mitigate supply issues, needs in the data, analysis, and tech development and demonstration (e.g., autonomous operation) remain.

## *Non-government Perspective*

### PAULA KEHOE
SAN FRANCISCO PUBLIC UTILITIES COMMISSION

Paula Kehoe is the Director of Water Resources with the San Francisco Public Utilities Commission (SFPUC) where she has served the city for nearly three decades.

Paula described challenges plaguing water and sanitation services, not just drought and aridification, but aging infrastructure, changing stormwater patterns, and in-stream flow needs.

San Francisco in response has led the way in the fit-for-purpose approach to recycled water at both centralized and decentralized scales for both potable and non-potable end-use across residential, commercial, and industrial sectors.

### ALBERT CHO
XYLEM, INC.

Albert Cho is the Senior Vice President and Chief Strategy and Digital Officer at Xylem, a global water technology company and serves on the Board of Directors for the U.S. Water Alliance.

Al envisioned an evolving nexus from water-energy to water-climate, as vital aspects of the future include both resilience and adaptation.

When looking at the lifecycle picture, several decarbonization pathways emerge. One such way is through optimization via operational data twins with decision support tools to enable system-wide efficiency; key to helping achieve a net-zero future for not just water but broader net-zero transitions.

### ANNE THEBO
PACIFIC INSTITUTE

Dr. Anne Thebo is a senior researcher at the Pacific Institute, a non-government organization focused on advancing solutions to the world's most pressing water challenges.

Anne focused her talk on the drivers, benefits, and tradeoffs associated with agricultural water reuse. Starting with the water source, one then must look at supply and timing, quality, and overall system connectivity.

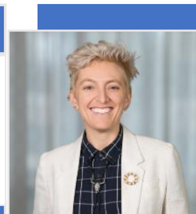
Municipal wastewater reuse for irrigation is much more widespread than commonly noted, but diverse barriers limit realization. Future work should look to supply, demand, and proximity to unlock full potential.

### CHRISTOBEL FERGUSON
WATER RESEARCH FOUNDATION

Dr. Christobel Ferguson is the Chief Innovation Officer at the Water Research Foundation (WRF) and has served over 30 years in the water and environment industry in both the U.S. as well as Australia.

Christobel identified five challenge areas for utilities: infrastructure, operations and management, economics, community engagement, and environmental systems.

She concluded by sharing WRF's highest ranked research needs: cost-competitive desalination, carbon diversion, fit-for-purpose water reuse, source separation, and energy/process optimization for onsite energy.



### ZOË ROLLER
U.S. WATER ALLIANCE

Zoë Roller is a Water Equity Fellow at the U.S. Water Alliance, where they explore the connections between water systems and racial/economic justice in the U.S.

Zoë's presentation offered a social perspective on the water equity problem, defining its indicators including the water access gap, aging infrastructure, affordability, and quality.

They emphasized the need for community-based and decentralized alternatives (with reduced risk) to traditional infrastructure and thinking about safe interim access to water while developing long-term solutions.

### JOHN WILLIS
BROWN AND CALDWELL

Dr. John Willis is a VP with Brown and Caldwell and Water Environment Federation (WEF) Fellow with over 31 years creatively attacking waste of energy and un-recovered resources within the wastewater space.

Focusing on centralized treatment, John highlighted ways to restock depleted soil carbon with biosolids, recover phosphorus or nitrogen, produce renewable energy, and beneficially recover resources.

Conclusion? Research still needed—GHGs from WRRFs are still not wholly understood and players from across stakeholder groups have yet to deliver success across the TRL spectrum.

# AMO Water and Wastewater RD&D Workshop Series

Tuesday, December 7th: 1:00 PM – 5:00 PM Eastern

Tuesday, December 14th: 1:00PM – 4:00 PM Eastern

Thursday, December 16th: 1:00PM – 5:30 PM Eastern

## Tuesday, December 7, 2021 (Week 1, Day 1 – Setting the Stage (RECORDED)

| | |
|---|---|
| **1:00 – 1:30 pm EST** | **Welcome and Department of Energy (DOE) Overview of Energy-Water Nexus Opportunities, Challenges, Current Activities, and RD&D Needs**<br>*Presenter: Melissa Klembara, DOE-Advanced Manufacturing Office (AMO)* |
| **1:30 – 2:30 pm** | **DOE Analysis in Water/Wastewater**<br>*Moderator: Jordan Macknick, National Renewable Energy Lab (NREL)*<br>*Panelists (10-15 min each):* |
| 1:30 – 1:45 pm *(15 min)* | • *Prof. David Sedlak, UC Berkeley – National Alliance for Water Innovation (NAWI) + High Technology Readiness Level Opportunities* |
| 1:45 – 2:00 pm *(15 min)* | • *Dr. Jennifer Stokes-Draut, Lawrence Berkeley National Lab (LBNL) and AJ Simon, Lawrence Livermore National Lab (LLNL) – Multi-lab Analysis Effort by AMO on Water/Wastewater Technologies* |
| 2:00 – 2:10 pm *(10 min)* | • *Dr. Prakash Rao, LBNL – Summary of AMO analysis on water/wastewater and resilience in manufacturing* |
| 2:10 – 2:30 pm *(20 min)* | Q&A |
| **2:30 – 2:45 pm** | **Coffee Break** |
| **2:45 – 4:15 pm** | **Plenary Session – Sector Stakeholder Perspective of Water/Wastewater RD&D Needs**<br>*Moderator: Mike Rinker, Pacific Northwest National Lab (PNNL)*<br>*Panelists (10 min each):* |
| 2:45 – 2:55 pm | • *Paula Kehoe, San Francisco Public Utilities Commission – big picture + San Francisco's decentralized portfolio* |
| 2:55 – 3:05 pm | • *Albert Cho, Xylem – digitization/Internet of Things for smart water* |
| 3:05 – 3:15 pm | • *Dr. Anne Thebo, The Pacific Institute – agricultural wastewater reuse* |
| 3:15 – 3:25 pm | • *Dr. Christobel Ferguson, The Water Research Foundation – municipal + building-scale water* |
| 3:25 – 3:35 pm | • *Zoë Roller, US Water Alliance – water access and social equity* |
| 3:35 – 3:45 pm | • *Dr. John Willis, Brown & Caldwell – big picture + industrial water* |
| 3:45 – 4:15 pm | Q&A |
| **4:15 pm - 5:00 pm** | **Wrap-up and Describe Agenda for Week 2 (Days 2 & 3)**<br>DOE explains the 4 breakout topics and rationale, then to decide the final topic for the 5th crowd-sourced breakout, the XLeap tool will be re-opened for attendees to brainstorm and vote for their favorite topic in real-time.<br>*Presenter: Melissa Klembara, DOE-AMO*<br>*Facilitator: Ross Brindle, Nexight Group* |

## Tuesday, December 14, 2021 (Week 2, Day 2 – Breakouts by Sector)

| | |
|---|---|
| **1:00 – 1:10 pm EST** (*5 -10 min*) | **Welcome and Today's Process and Recap of Day 1** |
| **1:10 – 2:30 pm** | **Breakout Session Pt. 1 – Real-time data/sensors/artificial intelligence (AI) and machine learning (ML)** |
| 1:10 – 1:20 pm *(10 min)* | DOE presents ideas synthesis to define the problem (3-5 slides) *– Led by Mike Rinker, PNNL and Madden Sciubba, DOE-Water Power Technologies Office (WPTO)* |
| 1:20 – 1:55 pm *(35 min)* | Mini Breakout Sessions |
| 1:55 – 2:30 pm *(35 min)* | Big Breakout & Report Back |
| **2:30 – 2:40 pm** | **Coffee Break** |
| **2:40 – 4:00 pm** | **Breakout Session Pt. 2 – Agricultural water and wastewater technologies** |
| 2:40 – 2:50 pm | DOE presents ideas synthesis to define the problem (3-5 slides) *– Led by Dr. Kimmai Tran, DOE-AMO and Sarah Barrows, PNNL* |
| 2:50 – 3:25 pm | Mini Breakouts |
| 3:25 – 4:00 pm | Big Breakout & Report Back |

## Thursday, December 16, 2021 (Week 2, Day 3 – Breakouts by Sector)

| | |
|---|---|
| **1:00 – 1:10 pm EST** | **Welcome and Today's Process and Recap of Day 2** |
| **1:10 – 2:30 pm** | **Breakout Session Pt. 3 – Municipal water, wastewater, and water reuse systems at all scales** |
| 1:10 – 1:20 pm | DOE presents ideas synthesis to define the problem (3-5 slides) *– Led by Melissa Klembara, DOE-AMO and Juliet Homer, PNNL* |
| 1:20 – 1:55 pm | Mini Breakouts |
| 1:55 – 2:30 pm | Big Breakout & Report Back |
| **2:30 – 2:40 pm** | **Coffee Break** |
| **2:40 – 4:00 pm** | **Breakout Session Pt. 4 – Small-scale water systems for rural/remote/native and other underserved communities** |
| 2:40 – 2:50 pm | DOE presents ideas synthesis to define the problem (3-5 slides) *– Led by Dr. Amanda Lounsbury, DOE-AMO and Dr. Rabia Chaudhry, Environmental Protection Agency (EPA)* |
| 2:50 – 3:25 pm | Mini Breakouts |
| 3:25 – 4:00 pm | Big Breakout & Report Back |
| **4:00 – 5:20 pm** | **Breakout Session Pt. 5 – Translating climate change impacts on water systems infrastructure and informing a circular water economy** |
| 4:00 – 4:10 pm | DOE presents ideas synthesis to define the problem (3-5 slides) *– Led by Melissa Klembara, DOE-AMO and Stephanie Kuzio, Sandia National Lab* |
| 4:10 – 4:45 pm | Mini Breakouts |
| 4:45 – 5:20 pm | Big Breakout & Report Back |
| **5:20 – 5:30 pm** | **Closing remarks** |

# Appendix B. List of Workshop Registrants

The following table is a list of workshop registrants who gave permission for their names, affiliation, and/or contact information to be shared.*

*Table 144: List of workshop registrants.*

| First Name | Last Name | Company/Organization | Email Address | Affiliation |
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| Iwnetim | Abate | UC Berkeley and MIT | iabate@mit.edu | Academia |
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* The authors of this report are not responsible for the accuracy of the information contained in the list of registrants. The information shown may be incorrect and/or incomplete due to human and/or machine error (e.g., spelling mistakes).

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# Appendix C. Additional Resources

The following table lists additional resources including reports and roadmaps with direct relevance to this workshop summary report.

*Table 15: List of additional resources with relevance to this report.*

| | |
|---|---|
| U.S. Department of Energy | The Water-Energy Nexus: Challenges and Opportunities (June 2014) |
| | Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems (Oct. 2016) |
| | Technology and Engineering of the Water-Energy Nexus (Oct. 2017) |
| | Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Seawater Desalination Systems (Oct. 2017) |
| | Evaluation of U.S. Manufacturing Subsectors at Risk of Physical Water Shortages (Feb. 2019) |
| | Water Security Grand Challenge: Workshop Outcomes (July 2019) |
| | Characterizing Manufacturing Wastewater in the United States for the Purpose of Analyzing Energy Requirements for Reuse (Mar. 2021) |
| | Future of Water Infrastructure and Innovation Summit: Workshop Report (May 2021) |
| | Survey of Available Information on U.S. Manufacturing Wastewater and Energy Requirements for Reuse (Sept. 2021) |
| | U.S. Manufacturing Water Use Data and Estimates: Current State, Limitations, and Future Needs for Supporting Manufacturing Research and Development (Sept. 2021) |
| U.S. Environmental Protection Agency | National Water Reuse Action Plan: Collaborative Implementation (Version 1) (Feb. 2020) |
| National Alliance for Water Innovation (NAWI) | NAWI Master Technology Roadmap (Aug. 2021) |
| | NAWI Technology Roadmap: Agriculture Sector (Revised Sept. 2021) |
| | NAWI Technology Roadmap: Industrial Sector (Revised Aug. 2021) |
| | NAWI Technology Roadmap: Municipal Sector (Revised Aug. 2021) |
| | NAWI Technology Roadmap: Power Sector (Revised Aug. 2021) |
| | NAWI Technology Roadmap: Resource Extraction Sector (Revised Nov. 2021) |
| The Water Research Foundation | Characterizing, Categorizing, and Communicating Next-Generation Nutrient Removal Processes for Resource Efficiency (2021) |

# Appendix D. Systems for Underserved Communities: Additional Stakeholders

Participants in the Small-Scale Systems breakout sessions responded to the following focus question:

***Who else should be included in this conversation of small-scale water systems for underserved communities?***

The following section lists all additional stakeholders as suggested by workshop participants:

- **Advocacy groups/coalitions for the homeless and unhoused**—Address technology and policy issues with drinking water, bathrooms, and showers
- **Public Hygiene Lets Us Stay Human (PHLUSH)**—Portland, OR-based group focused on urban public sanitation
- **International water NGOs**—e.g., Water.org, WaterAID (UK)
- **Locality-specific NGOs**—NGOs operated by locals with a sustained presence in the community
- Representatives of small communities
- **International groups with knowledge in decentralized systems**—Public education school systems and experts with knowledge of decentralized systems (e.g., prevalent in China and India)
- **U.S. Department of Agriculture (USDA)**—USDA has an existing rural water program
- Land-use planners, transportation, and infrastructure planners
- Tribal communities
- Rural Community Assistance Corporation (RCAC)
- Rural Community Assistance Partnership (RCAP)
- National Rural Water Association (NWRA)
- National Onsite Wastewater Recycling Association (NOWRA)
- American Rainwater Catchment Systems Association (ARCSA)
- U.S. Water Alliance
- Regulators and regulatory agencies
- City governments

- Water engineering firms
- **Local non-profits (e.g., Groundwork Denver in Denver)—**Organizations focused on access to water, energy, food, and transportation in urban neighborhoods
- National Association for the Advancement of Colored People (NAACP)
- **Local environmental justice groups**—e.g., Community Water Center (California)
- National Rural Electric Cooperative (NRECA)
- Health departments and related monitoring/testing program organizations
- **Private sector companies**—Businesses with operations in these communities (opportunities for co-funding)
- **Small-scale technology providers**—Providers of small-scale technology (e.g., Orenco Systems, AquaPoint)
- Consortium of Institutes for Decentralized Wastewater Treatment (CIDWT)
- Water Environment Federation’s *Small Community Committee*
- Jacobs Engineering and Engineers in Action

# Appendix E. Participant Comments and Endnotes

The following appendix lists additional comments, ideas, and anecdotal information offered by participants during the workshop series.

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[1] E.g., U.S. Food and Drug Administration (FDA), National Oceanic and Atmospheric Administration (NOAA), United States Department of Agriculture (USDA)
[2] New regulations for effluent treatment will set limits on total nitrogen (TN) and total phosphorous (TP).
[3] Participants specified that small-scale facilities qualify as having a rated design flow capacity of 5 million gallons per day (MGD) or less.
[4] According to participants, the National Rural Water Association (NRWA) employs energy efficiency technicians that are tasked with assessing and assisting energy efficiencies of community water and wastewater systems with populations of 10,000 or fewer. The NRWA, which conducts dozens of facility assessments per year, may have existing lifecycle data that could be useful to this specific opportunity.
[5] There are physical and maintenance challenges related to sensors in sewer collection system applications that need to be addressed.
[6] Claim from participant: Over 90% of GHG emissions from water utilities come from pumping water.
[7] Soft-start controllers may be a potential solution for reducing maintenance costs.
[8] E.g., Biosolids, secondary treated effluent, screen-trapped solids, recovered minerals including phosphorus and nitrogen-based compounds.
[9] E.g., U.S. grade standards for the quality of meat, maple syrup, and other regulated products.
[10] An alternative proposed R&D need in carbon diversion is a "carbon redirection battery" which would store wastewater carbon as an "on-demand" source of energy.
[11] Successful pilot programs for recovering thermal energy from sewage have been demonstrated in cities such as Seattle, and by organizations like the New York State Energy Research and Development Authority (NYSERDA).
[12] Participants note that the Department of Defense's (DOD) Environmental Security Technology Certification Program (ESTCP) and the State of California have a variety of technology demonstration funding mechanisms for emerging or challenging wastewater treatment issues.
[13] These data-driven models are sometimes referred to as "digital twin" models.
[14] E.g., centralized versus distributed; watertight effluent sewer systems versus traditional gravity sewers
[15] Participants noted that municipal wastewater reuse is rarely feasible without government subsidies.
[16] Micropollutants refer to contaminants in trace quantities (i.e., at or below the microgram per liter level).
[17] Participants also expressed concerned about the ability to properly dispose of CECs following recovery. Farmers do not have access to technologies that have been demonstrated to effectively treat CECs.
[18] In some places, farmers are unwilling to adopt sustainable water management practices due to a misconception that water reuse is associated with untreated sewage which therefore increases the risk of property devaluation.
[19] Refers to policies based on the "use it or lose it" adage.
[20] Note: The U.S. Department of Energy Bioenergy Technologies Office (BETO) is actively involved on related lifecycle assessments on biosolids reuse applications. DOE-AMO may be able to provide additional input.
[21] Parameters that inform the optimum installation of water harvesting technologies should consider geology, hydrology, and geochemistry of water and soil interactions.
[22] Nature-based agricultural solutions could potentially facilitate nutrient recycling, thereby offsetting synthetic fertilizer inputs.
[23] For example, the Federal government could bring together coalitions of crop- and dairy-based farmers to implement regional prototype systems for wastewater reuse using algae, cyanobacteria, and polycultures to improve water efficiency while recycling nutrients and preventing downstream algal blooms.
[24] "Modular" generally refers to systems that are easy to set up and configure to match a farm's specific agricultural needs.
[25] E.g., nitrogen, phosphorus, potassium.
[26] E.g., methane from biodigesters.

[27] Redundancy may help for periods of system maintenance or unexpected failure.
[28] Bio-digesters can enable methane production for dairies.
[29] Incentivizing participation in this type of demonstration effort is best achieved through collaborations and clusters. For example, producers in California's dairy industry collaborated to demonstrate bio-digesters to recover methane from waste. Another example of collaboration between farmers and industry includes beer production in which brewers provide spent grain to farms to feed to livestock.
[30] Case studies from advanced agriculture regions (e.g., Israel) could provide early answers to the impact of water reuse in intensified agriculture and could also steer research in less understood scenarios (e.g., recirculating aquaculture).
[31] Small communities that use decentralized systems can also benefit from 1.) full-service business models that include repair, maintenance, or replacement services (e.g., akin to residential or commercial propane tank exchange services), and 2.) access to information regarding the use of sensor and automation techniques.
[32] The EPA describes different small-scale water systems including for urban areas, centralized small communities, and remote areas with septic systems.
[33] Participants proposed opportunities as a function of these three specific community types. Each opportunity may be applicable to one or more of the other community types not specified by participants during workshop discussions.
[34] Many small-scale water treatment systems are not actively relying on newer water reuse and recycling approaches. However, potable water reuse systems will require thoughtful managerial oversight to ensure integrity and protect human health (i.e., to avoid a public crisis comparable to the Flint water crisis.)
[35] Regional consolidation is also generally referred to as regionalization.
[36] Includes rooftop-based rainwater harvesting configurations for urban areas.
[37] The Rural Community Assistance Partnership (RCAP)—a national network of nonprofit partners and technical assistance providers— and the National Rural Water Association (NRWA) are excellent resources but lack the capacity to fully address this problem. The Department of Energy (DOE) may be suited to provide some type of external engineering support.
[38] Participant designated the example as a "technologist/fellow in the community" program.
[39] State revolving funds (SRF) are based on federal-state partnership programs that provide communities with low-interest financing for making investments in water and wastewater treatment infrastructure.
[40] Native communities have strong drivers around land use and sovereignty. The broad water community could be more vocal in supporting indigenous Water Protectors and other activists working against threats to water supplies (pipelines, etc.).
[41] Old or aging water infrastructure can result in a decline in water quality caused by lead, heavy metals, and other contaminants of emerging concern.
[42] The *American-Made Challenge* is an example of an existing funding mechanism that awards funding for projects that seek to upgrades water treatment infrastructure.
[43] Participants indicate there is an opportunity to highlight examples of existing utility companies that have successfully implemented assistance programs that benefit low-income customers while supporting long-term infrastructure upgrades.
[44] This includes defining specific metrics with respect to the "low energy intensity" of the nutrient and pathogen removal technologies.
[45] Additional funding support may be required as some communities continue to struggle with paying loans on previous system upgrades.
[46] E.g., Low-cost greywater reuse systems.
[47] This opportunity is similar in nature to the World Health Organization's (WHO) global database(s) for monitoring water, sanitation, and hygiene (WASH) services.
[48] Detecting contaminants of emerging concern (CECs) and evaluating their impacts is under the purview of the EPA.
[49] Example parameters include physical (e.g., leaks), chemical (e.g., CECs; pollutants such as dissolved methane or carbon dioxide), and biological (e.g., bacterial, viral).
[50] Similar research and development efforts to this opportunity are being addressed at the Cybersecurity Manufacturing Innovation Institute (CyManII) and the Clean Energy Smart Manufacturing Innovation Institute (CESMII) under the Manufacturing USA program.

[51] There may be unmet opportunities for developers of cloud-based business intelligence tools to demonstrate the value of these tools more effectively to practitioners who will use them including managers, engineers, and operators.
[52] E.g., Entities may include U.S. Department of Interior's U.S. Geological Survey (USGS), and NOAA.
[53] According to census data collected by NOAA from 2014 to 2018, almost 40% of the U.S. population lived on the coast.
[54] According to the participant comments, utilities tend to conduct long-term resource planning in 5- or 20-year increments.
[55] Participants identified DOE Office of Science (SC), United States Geological Survey (USGS), and the National Oceanic and Atmospheric Administration (NOAA) as active developers of advanced large-scale climate prediction models.
[56] For example: moving toward greater efficiency from increase water reuse and treatment could cause issues such as degradation of chlorine residuals in standing water, and release of harmful gases from the decomposition of slow-moving sewage.
[57] The nature of this opportunity may encompass a research and development component.
[58] This activity may be within the purview of the Environmental Protection Agency (EPA).
[59] The Triple Bottom Line refers to social, economic, and environmental aspects.

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