



NSF Engineering Research
Visioning Alliance

Engineered Systems for Water Security

Visioning Event Report



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Executive Summary

Water security is fundamental to nearly every aspect of society. Despite this central role, both water infrastructure and management are fragmented, with nearly 150,000 public water systems in the United States. Within those systems, water is centrally managed, but separately from other utilities such as electricity. Integrated solutions are challenging when water providers operate as standalone entities with limited interactions with one another or with other stakeholders (e.g., industry, agriculture, energy). This fractured system leads to minimal communication and collaboration, even among neighboring jurisdictions, and limits the ability to predict the impact of decisions and implement actions. At the community level, residents of cities such as Flint, MI, and Jackson, MS, continue efforts to mitigate water quality and supply issues years after serious problems interrupted service delivery and shut down those systems. Water security is also impacted by water scarcity, with groundwater depletion rates threatening both domestic and international agricultural supply chains. Globally, climate change is creating more severe precipitation and drought cycles that further threaten water accessibility, with severe consequences anticipated by the end of the 21st century.

The United States is not immune to any aspect of water security risk; a 2021 study documented water hardship nationwide and found 1,165 community water systems in serious violation of the Safe Drinking Water Act. This same study found nearly 9%, or over 21,000 permittees, in significant noncompliance with the Clean Water Act. The Natural Resources Defense Council observed a strong relationship between communities of color (as well as those with low-income levels and greater numbers of non-native English speakers) and slow enforcement of the Safe Drinking Water Act. This is only one demonstrated instance of a long pattern of “environmental injustice” in the United States established along demographics of income, race and ethnicity, age, education, and rurality. Another study predicted that 92 of the 204 freshwater basins in the United States would experience annual shortages by 2070 due to climate change and population growth. One in five U.S. homes is not connected to municipal sewage systems. Although properly designed, operated, and maintained decentralized systems can be a critical part of the nation’s wastewater infrastructure, lack of access to centralized systems or optimized decentralized systems represents a failure of water security management.

Previous efforts to address water security have been stymied by the complexity of water policy issues and the patchwork of stakeholders and system funding mechanisms. Although it is not engineering’s role to address those complexities, focused efforts to leverage today’s confluence of research advancements in silicon chips and artificial intelligence, for example, offers a timely opportunity to gain traction and enable solutions. Effectively addressing climate change challenges and impacts such as flooding, droughts, and sea-level rise requires deliberate and knowledge-informed models and tools. The tools, technologies, systems, and management approaches discussed in this report can bring transformative change to the way society confronts water resource sustainability challenges and the impacts of climate change. With proper resource investment, advances in tools and technologies, including membranes, sorbents, sensors, and risk assessment and management frameworks can transform how society confronts looming threats to water security.

Research that will generate future engineered systems for water security must transcend the current social, ecological, and technological silos to enable the implementation of models described as “One Water System of Systems” or integrated water resources management (IWRM). IWRM is a cross-sector approach that recognizes the interdependence of all water use within local ecosystems. These integrated systems are envisioned as scalable, sustainable, and resilient. Such was the consensus of participants at a recent visioning workshop convened by the [Engineering Research Visioning Alliance \(ERVA\)](#) to identify roles for the engineering research community in achieving secure water systems for the future.

Engineering can lead the critical research efforts required to enable sufficient and safe water supplies for the next generation. Innovation is needed at all levels. While the term “water infrastructure” can encompass nearly everything discussed in the following pages, elements such as water harvesting and storage, contaminant detection and treatment, real-time tracking, predictive analytics/AI, and management frameworks have been discussed separately. Infrastructure is used here specifically to refer particularly to those physical components and processes relied on to pump, store, treat, conserve, and transport water, such as wells, dams, reservoirs, aqueducts, storage tanks, treatment units, and pipes.

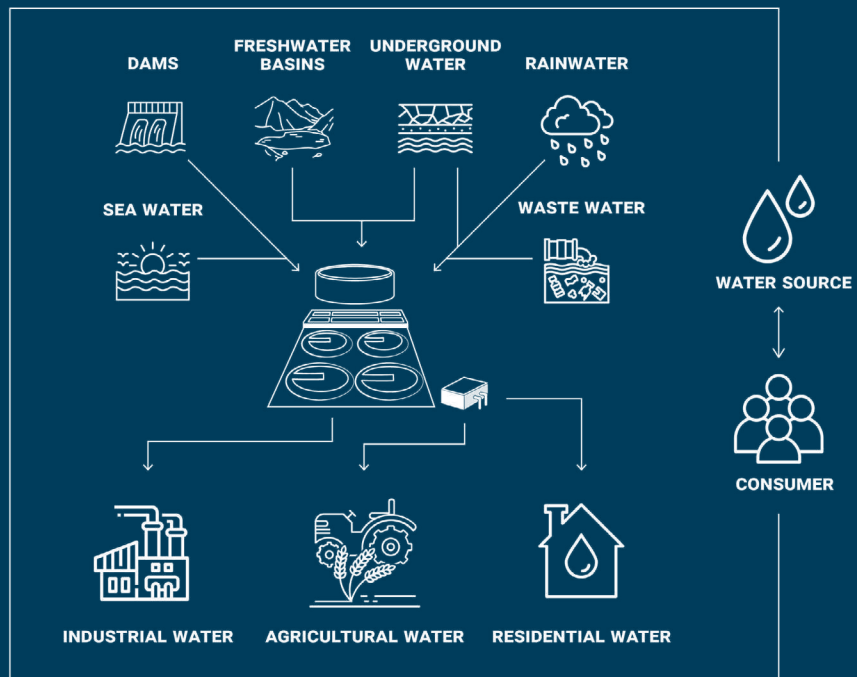
Future research will inform components, processes, and systems through development of new materials and technologies that are safe, sustainable, affordable, scalable, and adaptable. These new systems and technologies will spur equitable access to safe and plentiful water under both normal and stressed operating conditions to improve quality of life across communities.

Given the broad nature of the theme, this report is not intended to be an exhaustive exploration of potential engineering research directions for water security. Instead, five under-explored core engineering topics with substantial potential for impact are considered:

- **Increase affordability, reliability, and scalability of future components** of water systems for unit operations, including membranes, sorbents, and sensors to aid in water harvesting, contaminant detection, and treatment.
- **Create affordable, reliable, and scalable technologies** to visualize, maintain, and track physical components and water infrastructure processes.
- **Build new, resilient, and adaptable infrastructure** with the flexibility to opportunistically integrate legacy systems. Infrastructure solutions applicable across the continuum, from local-scale through basin/national scale, should be explored.
- **Improve data gathering and analysis and leverage predictive modeling and data-informed operations** for daily systems to long-term management, maintenance, and integration of water systems (drinking water, wastewater, stormwater, natural water resources). Use data-driven systems to monitor other water-dependent societal needs, such as energy and food, and leverage the data to enable hazard-resilient infrastructure.
- **Develop, test, and implement a water management framework** that considers the nexus between engineered, natural, and human systems. Such a framework aims to reduce multiple existing and emerging risks, increase efficiency and resilience of water services through new technologies, and enable robust, smart-systems adaptive decision-making.

The core topics above were shaped by an [ERVA Thematic Task Force](#), comprised of academic, corporate, and nonprofit experts, and explored by event participants. The resulting key priorities for engineering research investment cut across many aspects of water security, including systems design and operations technologies, infrastructure solutions, and infrastructure management. Each of these priorities contains numerous engineering research opportunities that will accelerate progress toward providing the United States with increased water security. These priorities are listed below and explored in the full report.

Integrated Water Systems



Key Priorities for Engineering Research Investment

- **Develop cutting-edge components** of water systems for unit operations, including membranes; sorbents that are bio-inspired, energy-efficient, low total cost, and low-carbon; and sensors to aid in water harvesting, contaminant detection, and treatment.
- **Develop efficient, cost-effective, easy-to-maintain, and practical decentralized water systems to improve local water security, including point-of-use, point-of-entry, and small-scale systems.** Envision and implement **new water collection systems, water treatment and distribution, and reuse** at multiple scales to enable broad uptake through demonstrated economic efficiency and effectiveness.
- **Design and implement scalable, resilient, integrated technological and decision-making water management frameworks** that consider the nexus between built, natural, and human systems.
- **Design scalable and affordable sensors, artificial intelligence (AI), and AI-informed technology** to improve real-time quality monitoring at scale while contributing to improved data-driven, predictive frameworks for decision-making. This includes **designing and building multi-scale digital models** to improve knowledge of whole-system behavior, reducing uncertainties in complex water systems and supporting decision-making across intersecting systems.
- Advance technologies and solutions for **water and resource recovery and reuse for manufacturing and agricultural production** that are water-efficient and optimize food, fiber, and energy uses.
- Create a **modular system-of-systems for resilient, adaptable next-generation water infrastructure** that is environmentally restorative and responsive to local needs. This hybrid model will enable centralized and decentralized solutions that are also cost-efficient, maintainable, and sustainable.
- **Assess and manage risk** to water supply and ecosystems in the move toward **minimal risk water**. There is a need to develop regional system-level water risk assessment and management frameworks and practical tools that consider the nexus of systems that interact with water.

Identified research priorities by time frame are detailed in Appendix A.

Taking Action

Future components of water systems must be developed for unit operations, including membranes, sorbents, and sensors to aid in water harvesting, contaminant detection, treatment, and recovery. These components must be affordable, reliable, scalable, and able to be integrated through an innovative system that facilitates visualizing, maintaining, and tracking water infrastructure physical components and processes. Components, processes, and systems must be energy-efficient and responsive to local and regional conditions. These developments will spur equitable access to safe and plentiful water under normal and stressed operating conditions.

Even as new technologies and processes are developed, research must continue into risk assessment and reduction so that communities not currently served by functional systems can access safe and sufficient water supplies and treatment for local use. Agricultural centers must require sustainable water use to grow safe food supplies. Rural areas need adequate clean water and safe wastewater treatment solutions that are economically viable, while urban systems must replace aging and inefficient technologies with more appropriate systems for current populations and needs. These solutions will require new technologies and improved decision-making tools that are automated, autonomous, and AI-informed. They will also require reconceiving infrastructure in both urban and rural areas in ways that respond to local natural and engineered conditions.

While legacy infrastructure must, in the short term, be repaired and upgraded to ensure water security, the development of hybrid resilient and adaptable infrastructure that enables centralized and decentralized solutions at scale is paramount. Such infrastructure will require both engineered and nature-based solutions, along with continued research to assess and define aspects of water quality needed for various purposes (human use versus agriculture, manufacturing, etc.). These characteristics must be delineated to determine how these uses can be applied in different systems and geographies.

It is critical to collect and integrate data to inform water infrastructure systems and operations. While components of water security systems measure particular aspects of their own operations (e.g., water treatment plants), data is not stored in common formats or shared among stakeholders, even in most local systems. Development of common, accessible databases and real-time dashboards for monitoring and managing systems should be prioritized, tested, and improved, with results shared widely. Specifically, data should be stored in AI-ready formats to assist in the modeling of complex system dynamics and assessment of the physical, environmental, social, and economic impacts of various water management strategies. New performance assessments will consider the combined intelligence of humans and algorithms to create more sustainable, cost-effective, and community-responsive water security systems.

Sustainable systems design and operations must be integrated across other core technological and social systems. Both life cycle assessment and techno-economic analysis must be applied to new components and systems to ensure their sustainability and cost-effectiveness. Interdisciplinary research is required to examine interdependencies between water systems performance impacts and other critical infrastructure. Development of next-generation decentralized and distributed water treatment systems, and their integration with nature-based solutions, should be explored to identify more cost-effective and resilient, scalable solutions.

Improving water security requires research across engineering disciplines and collaboration with experts in the social sciences, decision science, operations research, and humanities. It also necessitates increased collaboration between researchers and water industry practitioners to build greater trust and coordination to meet aligned goals for secure, safe, affordable water systems. Public opinion about water system management and quality assurance can improve with visible, effective system enhancements. When science, vision, and technology advancements converge in sustainable water infrastructure systems, the result will ensure safe and sufficient water for all.



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Our mission is to identify and develop bold and transformative new engineering research directions and to catalyze the engineering community's pursuit of innovative, high-impact research that benefits society.



**ERVA IS FUNDED BY THE NATIONAL SCIENCE FOUNDATION THROUGH
AWARD NUMBER 2048419**

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This material is based upon work supported by the National Science Foundation under Grant # 2048419. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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