NAWI

National Alliance for Water Innovation

AGRICULTURE SECTOR

TECHNOLOGY ROADMAP

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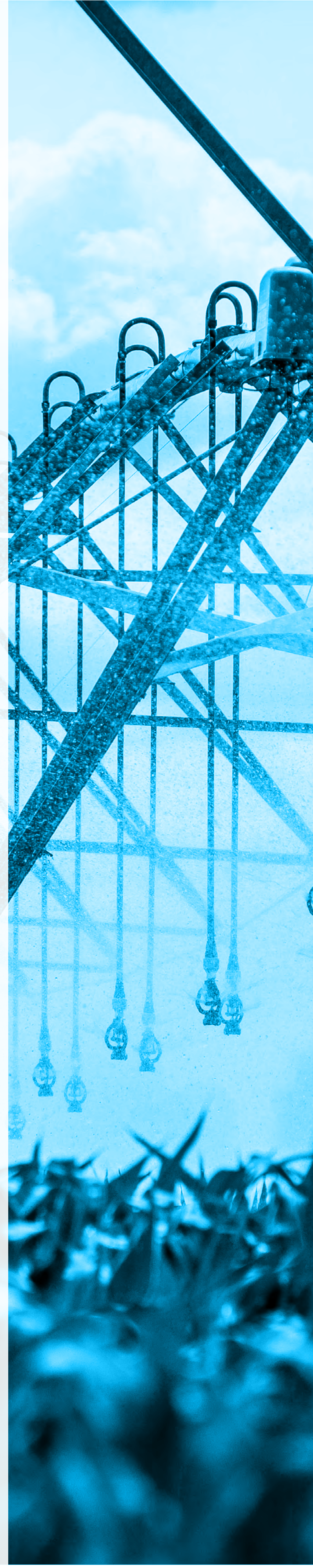

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This report, originally published in May 2021, has been revised in August 2021 to:

- Correct figure titles
- Correct Contributor names
- Correct grammatical errors
- Add new and deleted unused acronyms (Appendix A)
- Added the following sentence to page 5 to more clearly introduce Figure: "Across the sectors outlined above, the majority of freshwater withdrawals is used for irrigation (42 percent), followed by thermoelectric power (34.1 percent), as illustrated in Figure 2."

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1. EXECUTIVE SUMMARY

1.1 Introduction to NAWI and the NAWI Roadmap

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

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

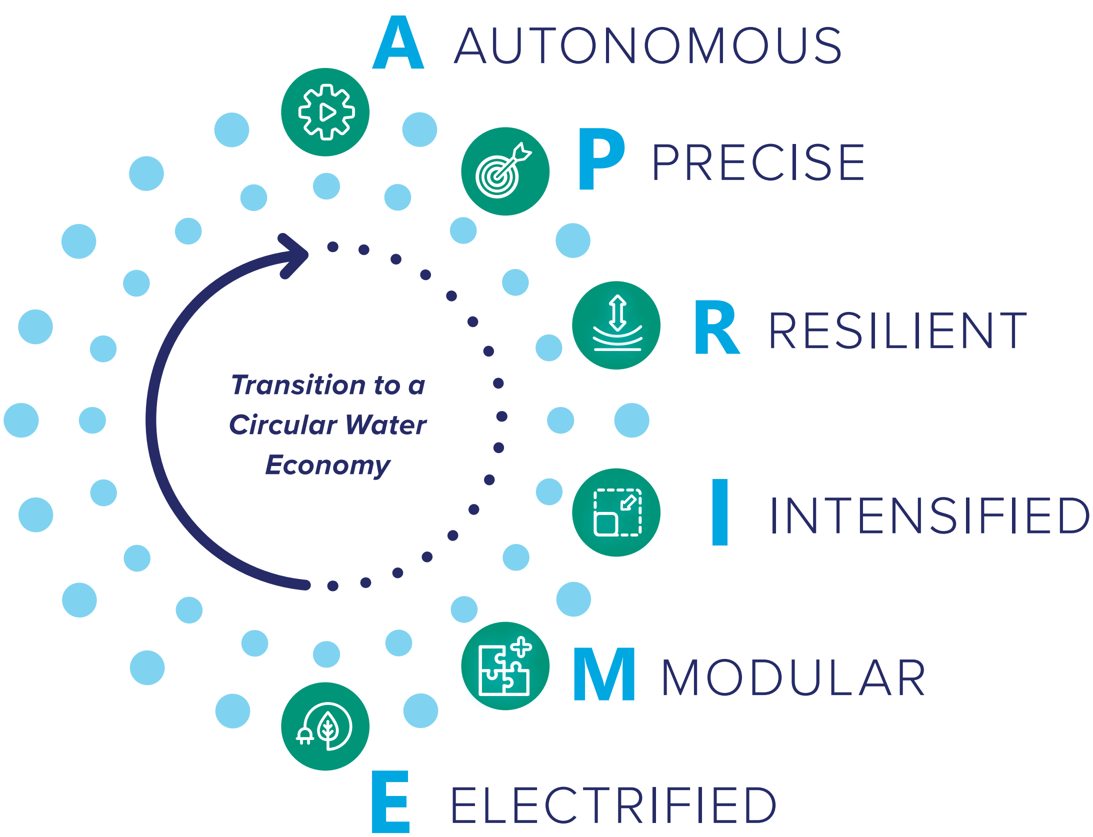
The nontraditional source waters of interest include brackish water; seawater; produced and extracted water; and power, mining, industrial, municipal, and agricultural wastewaters. When these desalination and treatment technologies are fully developed and utilized, they will be able to contribute to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

Power | **Resource Extraction** | **Industry** | **Municipal** | **Agriculture**

This **Agriculture Sector** roadmap aims to advance desalination and treatment of nontraditional source waters for beneficial use within the sector by identifying research and development (R&D) opportunities that help overcome existing treatment challenges.

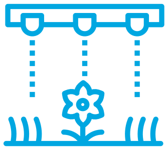
Under NAWI's vision, the transition from a linear to a **circular water economy** with nontraditional source waters will be achieved by advancing desalination and reuse technologies in six key areas: Autonomous, Precise, Resilient, Intensified, Modular, and Electrified, collectively known as the **A-PRIME**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

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



Pipe-parity is defined as the combination of technological solutions and capabilities (e.g., resiliency enablers and strategies leading to long-term supply reliability) and non-technological solutions that make marginal water sources competitive with traditional water resources for end-use applications. To effectively assess technology advances and capabilities, NAWI will use pipe-parity metrics relevant for the Agriculture End-Use Sector. These metrics can be quantitative or qualitative, depending on how an end user would evaluate different potential water sources and whether they could be integrated into their supply mix.

1.2 Water User Sector Overview



The Agriculture Sector is a significant water user in the United States; almost 280 billion liters (75 billion gallons) of water per day were used to irrigate over 200,000 farms in 2018. However, the demand for irrigation water in the United States is heterogeneous, varying with climate, time of year, crop type, and other factors.

In 2018, Western states, which typically have drier climates, accounted for 46.1 percent of harvested cropland but used 84.4 percent of irrigation water. In addition, meat and dairy processing consume 2.3 billion liters (620 million gallons) of water per day. Although this is considerably less than the amount of water used to irrigate crops, it is still important because, in many cases, wastewater from these processes may be more readily recycled than water applied to fields.

Fresh water, either from surface water or groundwater sources, is the primary source of agricultural water. The use of nontraditional waters for irrigation and food production has been considered in areas where freshwater is scarce. However, there has been limited implementation due to challenges including heterogeneous demand, broad geographic distribution of agricultural operations, wide variability in the quantity and quality of nontraditional source waters, and concerns about contaminants entering the food supply.

As the U.S. population grows, the agriculture industry is expected to expand production to meet domestic and international food needs while adapting to climate change and growing resource scarcities. Nontraditional source waters and recycling of water within farming and meat and dairy processing operations will play a bigger role in meeting agricultural water demands if desalination and advanced water treatment can achieve pipe parity.

1.3 Water Treatment and Management Challenges

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

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

TECHNICAL

Water Supply and Quality

- Presence of chemical and microbial contaminants in nontraditional source waters such as selenium (Se), boron (B), arsenic (As), and waterborne pathogens, at concentrations that can endanger human health, impact receiving water or compromise food production
- Varying proximity and accessibility to nontraditional water sources, which could limit the integration of these sources into the water supply mix for agriculture
- Large-scale regional and even site-to-site variability, along with seasonal variability in agricultural water demand, as well as limited land availability for the surface water storage of nontraditional waters (e.g., ponds and reservoirs) to meet temporal demands
- Low-cost water from traditional sources in many locations

Source Water Treatment Limits

- Inefficient removal of agricultural-relevant contaminants found in nontraditional water sources
- Limited options for treating brines (i.e., water with high concentrations of salts) produced in meat and dairy processing operations, irrigation, and water recycling for agricultural purposes

Resource Recovery and Waste Management

- High costs and limited options for disposal of concentrated waste streams produced in meat and dairy processing operations
- High costs and limited options for management of brines and residuals produced by desalination processes

Materials Capability and Durability

- A high tendency for unconventional waters of interest for agricultural system to cause fouling and scaling of treatment devices, piping, and irrigation systems, which impact the stability, lifespan, and durability of Agriculture Sector water infrastructure

Toxicology

- Nontraditional water sources for agriculture, which often consist of complex matrices that complicate assessment of potential risks to human health, livestock, crops and the environment

Land Availability

- Limited land availability for agricultural natural treatment systems, such as constructed wetlands

NON-TECHNICAL

- Potential negative cultural and societal attitudes about the consumption of agriculture products produced with nontraditional source waters
- Water laws in some states, particularly in the Western United States, that might limit the diversion or storage of water for new uses, including reuse for irrigation
- Other rules, regulations, and laws concerning the use of nontraditional water sources for agricultural, dairy, and livestock businesses, including food safety rules
- Various environmental factors, including droughts and changing weather patterns, which can limit access to nontraditional water sources

1.4 Research Topics

To overcome these industry challenges, advance pipe parity, and achieve NAWI's mission of expanding the use of nontraditional source waters for the Agriculture Sector, this roadmap lays out several research priorities that were identified through structured roadmapping processes with subject matter experts. These R&D Areas of Interest (AOIs) are grouped under the individual A-PRIME categories discussed earlier. Specific research gaps (i.e., a technology or problem that has not been sufficiently explored by existing studies) are also included with each development area. At the end of this summary of topics, a short discussion on the benefits of new techno-economic analysis and life-cycle analysis is also provided.

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

- **Develop and use rapid, real-time, low-cost sensor groups and associated monitoring and control systems to detect target pollutants/constituents** (e.g., pathogens, Se, B, As, phosphorus [P], and nitrogen [N]), with a focus on elements with fluctuating and wide ranges of concentrations. Treatment and reuse of agricultural water with high temporal changes in water quality require real-time feedback for optimization of treatment, precision irrigation, and accurate blending of the treated water with other water sources; these capabilities are currently not viable. Therefore, there is need for sensor technology that can detect key agricultural constituents such as As, Se, B, pathogens, nutrients, pesticides, antimicrobials, organic matter, and algae.
- **Apply machine learning models and algorithms to data from sensors and other sources to develop agricultural quality standards for process waters and source waters, and to minimize the costs of alternative source water treatment, storage, and delivery.** Alternative source waters must meet agricultural water quality requirements at costs that are competitive with traditionally used ground and surface water sources and that are consistent with the market values of irrigated crops, meats, and other agricultural products. Machine

learning is already used in wastewater treatment to monitor influent conditions, optimize maintenance and treatment parameters, and predict effluent concentrations. Machine learning models and algorithms have the potential to provide more specific source water treatment criteria, and to make the use of alternative source waters in agriculture more cost-effective.

- **Develop automated digital network systems** (e.g., the Internet of Things [IoT], supervisory control and data acquisition [SCADA], digital twins, artificial intelligence [AI]) for integrated water quality data analysis, data-driven decision making, process monitoring, and control for optimized water and wastewater treatment. Without effective automated digital networks, there will be continued costly onsite and manual interventions. With effective automated digital networks, dynamic control of water and wastewater treatment systems is possible. These capabilities are necessary for growers, ranchers, and producers to tend to agricultural spaces that have large-scale regional and even site-to-site variability along with geographically distant features.

- **Develop an autonomous system that optimizes the procedure of membrane cleaning and membrane replacement during desalination of agricultural wastewater.** Meat and dairy processing wastewater desalination technologies are challenged with the need for daily and more intense periodical cleanings due to the presence of foulants (e.g., proteins in meat processing wastewater). The technologies implemented require flushing and cleaning processes to mitigate fouling and sludge buildup in the systems. Affordable pre-treatment and autonomous cleaning technologies that relieve the need for frequent maintenance are required to advance desalination processes (e.g., to pre-emptively remove oxyanions, emulsified oils, and other constituents that increase the need for cleaning).

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

- **Develop low-cost, selective separation technologies to remove contaminants that can adversely affect agricultural production or meat and dairy processing or negatively impact public health and/or agro-ecosystems.** The main challenges with treating nonconventional sources for application in agriculture are the high total dissolved solids, high organic content, and poor removal of constituents in processes targeting bulk water treatment. This research area targets and selects those with unique importance within agriculture (e.g., B, Se, As, and oil and grease). Selective separation of contaminants will mitigate the negative environmental and public health impacts of utilizing improperly treated water and will present an opportunity for valuable resource recovery.

- **Develop low-cost and selective separation technologies for the valorization of agricultural wastewater** (e.g., meat processing wastewater, tile drainage). Current treatment technologies for these wastewaters are typically unsuccessful in the recovery of constituents necessary for waste-stream valorization. For the meat processing industry, the challenges include removing proteins and organics in pre-treatment, improving the concentration of solids in effluents after desalination, and removing high amounts of N. Selective removal of N and P could result in beneficial reuse in agriculture through the production of fertilizer. For tile drainage reuse, the challenge of valorization is removing toxic constituents that could enter the food system or could impact crop and soil health (e.g., total dissolved solids [TDS], total suspended solids [TSS], heavy metals, pathogens, Se, As, B, and persistent organic pollutants) while leaving other valuable nutrient products in the water (e.g., nitrate [NO_3^-], phosphate [PO_4^{3-}], potassium ions [K^+], magnesium ions [Mg^{2+}], and calcium ions [Ca^{2+}]).

- **Develop high-performing and cost-efficient materials for precision separation and easy in situ regeneration, such as adsorbents** (e.g., modified zeolite, metal organic framework materials), ion exchange resins, and membranes. Materials that can perform solute-selective separations still present immense challenges for water reuse. Research should focus on relating material properties (e.g., solute/ligand binding constants, uptake capacities) to overall performance (e.g., regeneration potential and frequency). Multifunctional materials can also be leveraged to achieve solute-specific separations through several mechanisms.

- **Explore selective removal of sodium ions (Na^+) and chloride (Cl^-) using electrochemical/electro-membrane processes to reduce the Sodium Adsorption Ratio (SAR) for irrigation or recover salt and add back to brining during meat processing.** High amounts of Na^+ and Cl^- in nontraditional water can cause salt accumulation in soil and damage plants during irrigation due to soil sodicity and chloride toxicity. Studies should be initiated to: 1) understand the physical, electrochemical interactions of the membranes/materials with electrolytes, and 2) understand transport models to simulate and predict the permselectivity of the membranes over a range of electrical potential, varying water composition, and operating conditions. With improved understanding of these phenomena, research should focus on developing low-cost highly selective resins, membranes, or electrodes for the selective separation of Na^+ and Cl^- from other monovalent and multivalent ions.

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

- **Develop technologies that do not use chemicals, that reduce chemical consumption, or that are based on in situ generation of chemicals to minimize chemical transport, storage, and handling.** Treating nontraditional water sources for irrigation purposes often requires the addition of chemicals, which need to be transported and stored. Advanced treatment technologies bring new challenges related to on-site storage of hazardous unstable chemicals, transportation, and tail waste management.

- **Develop dynamic biological treatment systems that are resilient to variations in water quality, temperature, and toxins.** These systems should also be optimized for recovery or transformation of nutrients and removal of contaminants of emerging concern (CECs). The efficient and stable performance of conventional wastewater treatment processes depends on the influent quality (e.g., presence of toxic emerging contaminants and pathogens) and environmental conditions. Recent development in agro-based adsorbent materials could reduce the risk of pathogens and toxic and/or refractory organic pollutants from nontraditional water prior to its use for irrigation. It also could help recover nutrients for agricultural uses.

- **Develop technologies for effective water treatment and monitoring that will allow sustainable long-term storage of agricultural water in aquifers and ponds.** Long-term storage of water and real-time monitoring via sensors will require technologies that are low-maintenance and resilient under conditions encountered in the natural environment. These systems need to conduct remote, real-time analysis of stored water so users can monitor variables including nutrient loads, salinity, and pesticide concentrations. With reliable storage capabilities, water can be pumped upstream to irrigation systems and reapplied to fields when natural precipitation is insufficient.

- **Develop engineering and materials science approaches that address material/system stability, lifetime, and durability challenges based on mechanistic understanding of degradation, stability, and durability.** Meat processing and municipal wastewaters often contain abundant nutrients that could be beneficial for agricultural irrigation. However, these sources have a higher fouling potential due to the presence of diverse organic and biological foulants. The current progress on fouling- and scaling-resistant materials are not tailored to the Agriculture Sector. Therefore, developing novel materials that adapt and are compatible with the complex compositions of relevant source waters is essential to the practical implementation of water and wastewater treatment systems.

- **Develop more reliable low-energy natural systems** (e.g., resilient engineered wetlands), enabling an effective response to varying water quality and quantity. Land requirements and the inconsistent performance of natural treatment systems currently limit their wider adoption in agriculture. Engineered wetlands that can operate under seasonal changes while maintaining constant removal rates of agriculture-relevant constituents (e.g., nutrients, organic contaminants, and pathogens) under different conditions (e.g., seasonally, under varying flows) are needed.

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

- **Develop technologies for cost-effectively producing and managing low-volume, high-concentrated brines or other forms of desalination waste to avoid the use of dilution for their disposal.** Incorporating advanced desalination treatment technologies for brine management from agricultural wastewater (e.g., wastewater from meat processing and dairy processing, such as cheese-making) has proven to be a barrier. Current practices of blending freshwater with saline agricultural drainage or using high-quality water to dilute brine and produce water may not be economically feasible nor suitable for long-term and sustainable irrigation use. Developing high-performance zero-liquid discharge (ZLD) systems and renewable energy-driven brine treatment systems is essential to the sustainability of agricultural operations.

- **Establish systems to manage, recover, and create/improve the value of nutrients and residuals for fertilizers, such as lithium (Li)** (e.g., from produced water), Se (e.g., from tile drainage), proteins (e.g., from meat and dairy processing) and other materials for new uses. Numerous efforts have attempted to advance nutrient recovery (especially N and P) capabilities, but the thermodynamic and operational limitations of these processes for high-salinity waste streams are poorly understood. Developing effective removal and recovery processes provides the opportunity to reduce high concentrations of constituents for waste disposal and a marketable product with economic benefits.

- **Develop advanced modeling and in operando monitoring tools to understand precipitation, nucleation, crystallization, solute activity, and heat transfer in high-salinity waters to control scaling and intensify process design for brine treatment.** Scaling caused by precipitation of sparingly soluble salts can significantly hinder the brine treatment and impair efficiency. Further, the constituents of brines vary drastically depending on their sources and processes used upstream, making brine management challenging, as there is no universal method available. New thermodynamic and kinetic models need to be developed based on water chemistry, temperature, pressure, and other considerations. The new models could inform the design and operation of brine treatment processes.

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

- **Develop high-rate and high-recovery desalination processes for agricultural applications using a range of approaches, such as electrodialysis.** Desalination of nontraditional water such as brackish water and meat and dairy processing wastewaters requires low-cost, high-rate, and high-recovery technologies for agricultural applications with minimal waste disposal. The selection of desalination technologies should consider the capital and operational costs, energy efficiency, reduced costs for concentrate disposal, and savings from the recovery of additional water and fertilizer from using selective desalination technologies.

- **Create a hybrid system combining wastewater treatment with onsite production of fertilizers** (e.g., osmotic membrane, electrochemical processes, ion exchange, pervaporation). Current fertilizer production is energy-intensive and heavily relies on finite mineral resources. Recovery of nutrients from waste streams provides a promising strategy for more sustainable wastewater treatment and agriculture.

- **Develop small-scale modular desalination technologies that operate on electricity, renewable energy, or waste heat to remove salts and proteins.** Small-scale desalination technologies are less prevalent due to challenges associated with managing the low volumes of highly concentrated brines that are generated. Small-scale desalination equipment is not commercially available, but it could benefit the Agriculture Sector particularly to desalinate meat and dairy processing wastewater.

- **Develop and integrate beneficial modular designs in engineered natural treatment systems** (e.g., modularity with natural systems). Constructed wetlands have been used to treat a variety of agricultural wastewaters. These natural biofiltration treatment systems are self-maintaining and can provide active storage for water during dry seasons. However, there is a need for modular and climate-resilient wetland designs that can achieve higher removal efficiencies and can adapt to variations in the influent water quality, water temperature changes, and agricultural end-use needs.

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

- **Develop innovative materials for advanced electro-membranes, electrocatalytic, and bio-electrochemical systems that can be used for pretreatment** (e.g., chemical-free scaling and fouling control, pH adjustment), treatment (i.e., removal of contaminants), and post-treatment (e.g., ultraviolet/light emitting diode [UV/LED] Advanced Oxidation Processes [AOPs]) to improve system performance and reduce costs. The large-scale applications of current electro-processes have been limited by high cost, instability, poor understanding of capabilities and limitations, and relatively high energy intensity. When these technologies come to fruition, they will have several advantages, including high separation efficiency, low energy consumption, and modularization.
- **Integrate renewable/alternative energy with electrified desalination and related processes for remote and farm locations.** Develop techno-economic models to quantify the synergies between these two systems as well as the benefits gained in stability, reliability, and flexibility derived from electrification. Delivering reliable electricity supplies to electrified desalination and related processes in remote and farm locations can be both a logistical and economic challenge. Renewable energy technologies and other alternative sources, such as solar, wind, hydro, geothermal, and biomass, are great candidates to meet this need because of their versatility in this space.
- **Develop technologies to concentrate contaminants for more efficient treatment** (e.g., smaller volumes, higher removal rates) by electrochemical and electrocatalytic processes. Agricultural-relevant contaminants in nontraditional source waters need to be concentrated to achieve efficient removal. For example, persistent organic pollutants in municipal wastewater are present at trace concentrations. Their low concentrations result in slow kinetics of transformation reactions, decreasing the treatment efficiency and increasing treatment costs. Concentrating contaminants prior to electro-treatment processes is pivotal to improve the kinetics of contaminant removal and achieve more efficient treatment at substantially reduced costs.
- **Improve energy efficiency by waste heat recovery and systems optimization of electrified driven processes** (e.g., recover heat from boiler water or engines used in meat and dairy processing). Current desalination systems (e.g., mechanical vapor compression [MVC], membrane distillation [MD]), can be very energy intensive. Waste heat recovery can help reduce the electrical/thermal energy requirements. Recovering waste heat from various operations in meat and dairy processing (e.g., hydraulic systems and boilers) could be used to pre-heat wastewaters entering treatment systems, requiring less energy.

Improving the economic viability of treatment systems that can treat to the level needed for municipal applications could enable a transition to other advanced treatment technologies.

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

- **Valorization of Treatment By-Products:** Part of the treatment cost of water could be offset by valorization of the treatment by-products. The by-products could be sold or even reused on-site (e.g., salt reuse in meat processing applications, nutrient recovery from municipal wastewater, and recovery of rare minerals from produced water) to strengthen the economic viability of treatment systems.
- **Evaluation of Technologies used in Treatment:** Development of new approaches that reduce cost while maintaining sufficient performance may enable more attractive treatment technologies and increase the likelihood of future commercial adoption compared to complex, expensive treatment options.
- **Implementation of Alternative Energy Sources:** Many water treatment systems ultimately depend on non-renewable energy sources (e.g., petroleum, coal, and natural gas). The economic viability of water treatment for use in agriculture can be improved with the utilization of low-cost renewable and/or normally wasted energy sources.
- **Evaluation of Treatment Trains:** Waste streams from similar sources from different locations (e.g., waters from different tile drainage regions) and multiple streams from different sources on one site (e.g., streams from separate processes in meat processing plants) can have different constituents and concentrations. Optimization of the treatment process for that target source water can enable higher implementation rates of new treatment technologies.
- **Consideration of Environmental Impact:** Environmental performance of a treatment train must be evaluated for the different nontraditional source waters (e.g., releases to air, water, and soil). Other environmental impacts include climate change (e.g., carbon footprint, greenhouse emissions) and eco-toxicity (e.g., eutrophication). LCA can be used to quantify these undesirable effects.

1.5. Next Steps

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

1.6. Appendices

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

2. INTRODUCTION

2.1. Growing Challenges with Water

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

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

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

2.2. Establishing an Energy-Water Desalination Hub

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

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

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

2.3. Pipe Parity and Baseline Definitions

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

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

Specific pipe parity metrics of relevance can include:

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

Reliability and Availability

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

Compatibility

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

Sustainability

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

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

Specific baseline information required includes:

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

2.4. Nontraditional Waters of Interest

2.4.1. Sources of Nontraditional Waters

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

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

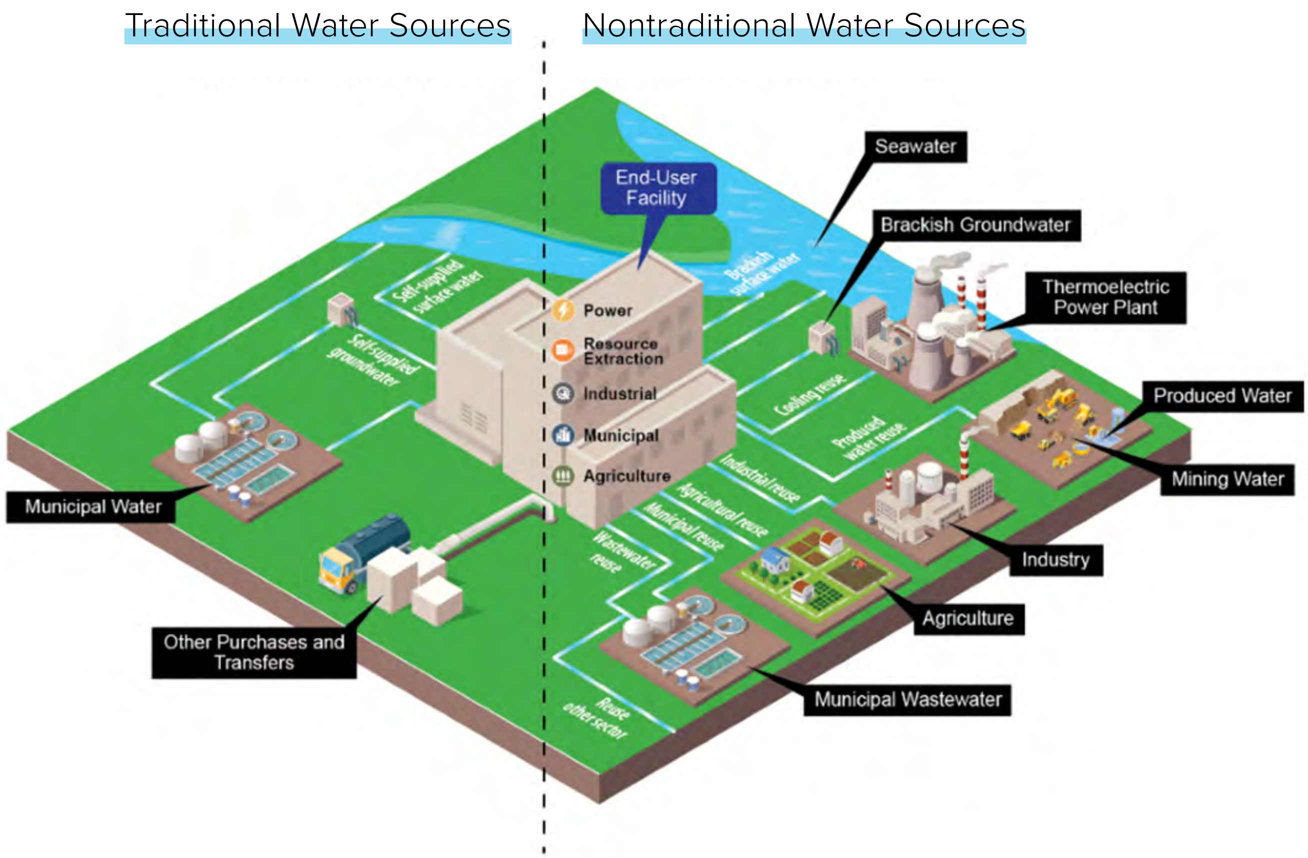


Figure 1. Schematic of traditional and nontraditional sources of waters, as defined by NAWI
(Graphic courtesy of John Frenzl, NREL)

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

2.4.2. End-Use Areas Using Treated Nontraditional Source Waters

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

NAWI identified these broad "PRIMA" sectors because they are major users of water with opportunities for reuse. Figure 3 expands on the industries included in NAWI's PRIMA broad end-use sectors. These areas are not meant to be exhaustive, as nearly all industries and sectors rely on water in one way or another.

Power

Water used in the electricity sector, especially for thermoelectric cooling

Resource Extraction

Water used to extract resources, including mining and oil and gas exploration and production

Industrial

Water used in industrial and manufacturing activities not included elsewhere, including but not limited to petrochemical refining, food and beverage processing, metallurgy, and commercial and institutional building cooling

Municipal

Water used by public water systems, which include entities that are both publicly and privately owned, to supply customers in their service area

Agriculture

Water used in the agricultural sector, especially for irrigation and food production

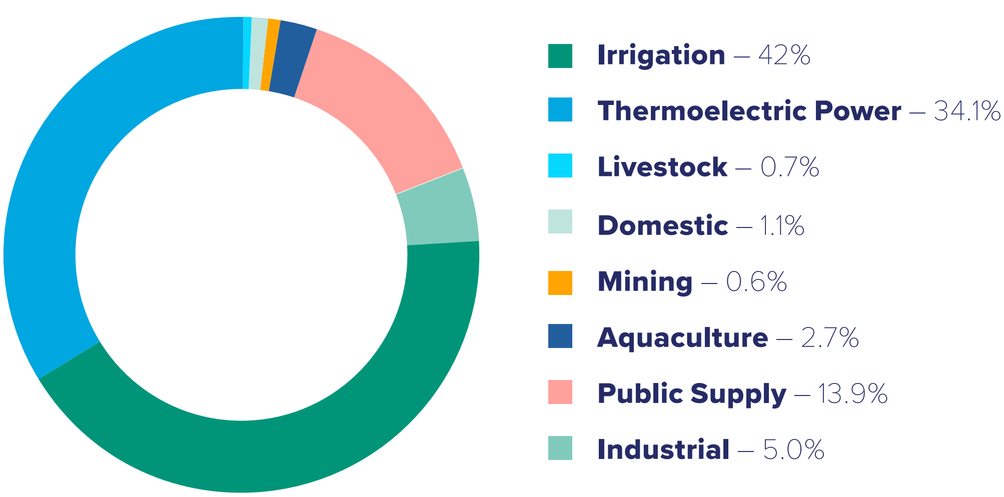


Figure 2. Freshwater withdrawals by water use category[5]

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

Figure 3. PRIMA and the industries covered in each area

2.5 A-PRIME

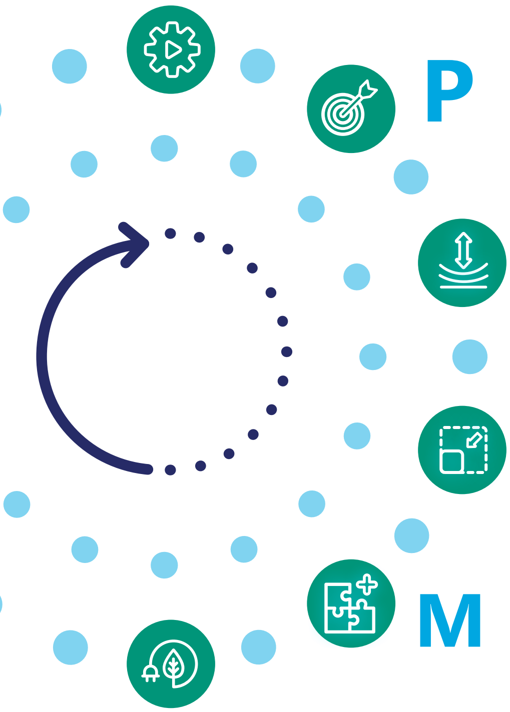
Securing water supplies for multiple end uses requires technology revolutions that will transition the United States from a linear to a circular water economy.

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

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

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

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



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

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

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

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

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

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

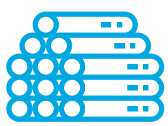
2.6. Desalination Hub Topic Areas

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

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

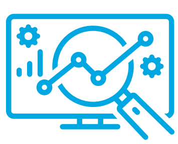
Process Innovation and Intensification R&D

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



Materials and Manufacturing R&D

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



Data, Modeling, and Analysis

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

3. AGRICULTURE WATER USER SECTOR OVERVIEW

This overview of the Agriculture Sector is meant to provide a high-level synopsis of the industry and provide insight and a rationale for this roadmap's focus—expanding the availability and reliability of nontraditional source waters for agricultural operations.

3.1. Water Demand in Agriculture

U.S. agriculture produces hundreds of billions of dollars in crop and animal products every year, providing affordable food for domestic needs and export across the world.

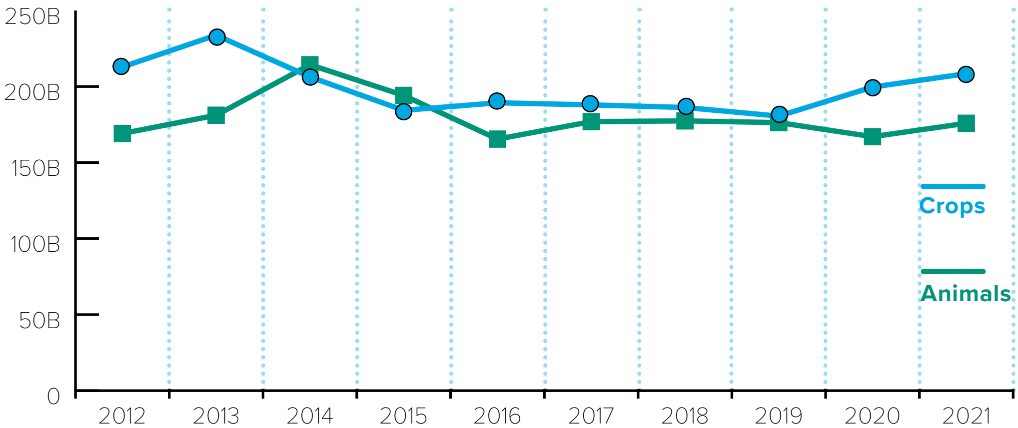


Figure 4. Value of crop and animal production for the United States[6,7]

Data Source: USDA's ERS (Feb. 2020)

The agricultural industry is a major water user in the United States, notwithstanding the fact that precipitation satisfies a large portion of the agricultural water demand. In 2017, there were more than 364 million hectares (900 million acres) of land in U.S. farms and more than 129 million hectares (320 million acres) of harvested cropland.[8] The 2018 Irrigation and Water Management Survey (IWMS)[9] reported that 102.9 billion cubic meters (83.4 million acre-feet) of irrigation water were applied to 22.6 million hectares (55.9 million acres) in 231,474 farms, at an average of 4,572 meters cubed (m^3) per hectare (1.5 acre-feet per acre).[‡] This equates to 102.9 trillion liters (27.2 trillion gallons) of water per year, or 281.6 billion liters per day (BLD) or 74.4 billion gallons per day (BGD). The top five states in irrigated acres and irrigation volumes were:

STATE	IRRIGATED ACRES
California	**8.4** million
Nebraska	**7.7** million
Arkansas	**4.2** million
Texas	**4.1** million
Idaho	**3.4** million

STATE	IRRIGATION ACRE-FEET
California	**24.5** million
Idaho	**6.6** million
Texas	**5.3** million
Arkansas	**5.1** million
Nebraska	**4.9** million

‡ An acre-foot of water is the quantity of water required to cover one acre to a depth of one foot, and is equivalent to 43,560 cubic feet or 325,851 gallons.

A large fraction of applied irrigation water is lost to evapotranspiration and other consumptive uses. In fact, the United States Geological Survey (USGS) estimates that 62 percent of the applied irrigation water is consumptively used. The remainder returns to surface or groundwater or is collected for recycling in irrigation. **Agriculture is a major national consumer of groundwater and surface water, accounting for 80 percent of the nation's consumptive water use and over 90 percent in many Western states.**[10] This roadmap will consider both withdrawals and consumptive uses.

The demand for agricultural irrigation water in the United States is heterogeneous. The volume of required water varies with crop type, growth stage, climate, and the timing and amount of precipitation, which affect the amount of water consumed through soil evapo-ration and plant transpiration (evapotranspiration demand).[11] Crop yields are reduced when evapotranspiration demand is not met, especially during critical growth stages.[12] In addition, salt accumulation in the root zone adversely affects crop yields in some locations, inhibiting seed germination, altering water uptake, and causing ion-specific toxicities or imbalances.[13] As a result, additional water may be required to leach salts from the root zone, or for purposes such as field preparation, chemical application, or frost protection.

These factors lead to different irrigation demands at different places and times throughout the United States. In 2018, the 17 Western States, which contain 46.1 percent of the harvested cropland[14] accounted for 72.1 percent of the irrigated acres and 84.4 percent of the irrigation volume.[15] Similarly, they accounted for 81.1 percent of all freshwater withdrawals for irrigation in 2015 (Figure 5).[16]

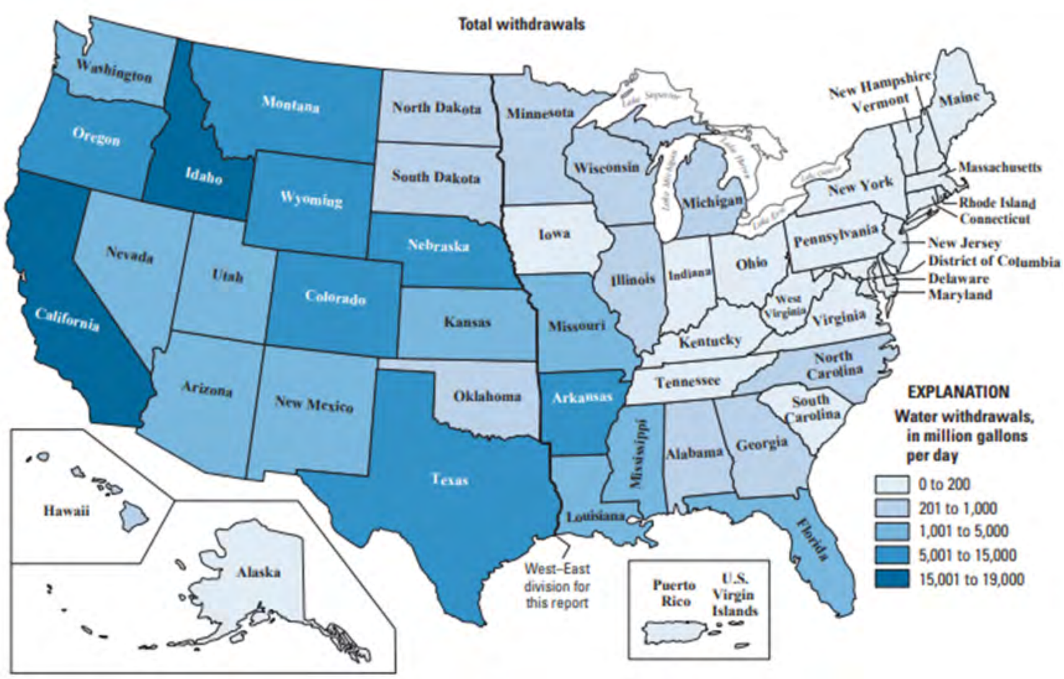


Figure 5. Irrigation water use by source and State, 2015
(Source: USGS

Agricultural water use is not limited to crop and horticultural production. The USGS estimated freshwater withdrawals for livestock at 7.6 BLD (2.0 BGD), including water used in feedlots and dairy operations.[17,18] In addition, meat and dairy processing withdraw 1 trillion liters (266 billion gallons) of water and produce 2.6 trillion liters (689 billion gallons) of wastewater annually, equivalent to 0.5 percent of the total U.S. water withdrawals (Figure 6).[19] Moreover, meat and dairy processing plants are often located in places where the irrigation demand is already high (e.g., Colorado, Nebraska, Arizona, Utah, Texas, and California).[20,21] While meat processing plants are net-zero water consumers, dairy processing is a significant net producer of water. Final cheese products weigh roughly 10 percent of the raw milk used to produce it.[22] The rest of the milk product, cheese whey, is added to wastewater streams, making milk processing facilities as a whole produce more water than consumed.

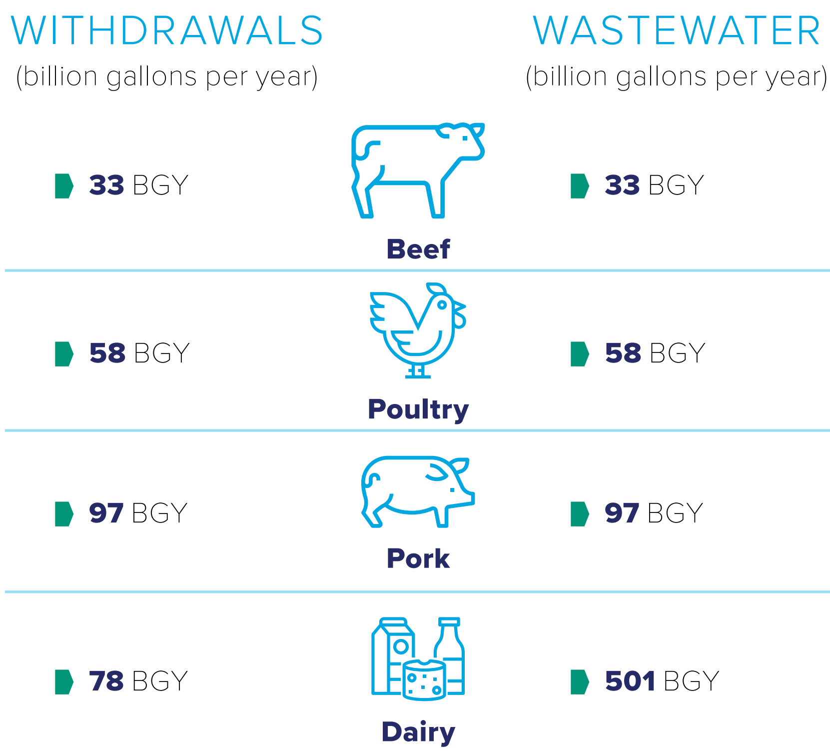


Figure 6. Volumes of water withdrawn and wastewater produced in beef, poultry, pork, and dairy processing annually in the United States
(Graphic courtesy of Thomas Borch, Colorado State University)

3.2. Water Supplied to Agriculture

3.2.1 Traditional Sources: Surface and Groundwater

Surface and groundwater are the traditional sources of agricultural water. Their proportions vary from state to state, but their proportions of freshwater withdrawals for irrigation across the United States were approximately equivalent (51.6 percent surface water vs. 48.4 percent groundwater) in 2015.[23]

Surface waters include existing networks of streams, ditches, canals, reservoirs, and other water bodies capable of transporting irrigation water across vast distances. The 2018 IWMS divides surface water into on-farm and off-farm water. "On-farm surface supply" is water from a surface source not controlled by a water supply organization, including streams, drainage ditches, lakes, ponds, reservoirs, and on-farm livestock lagoons on or adjacent to the operated land.[24] "Off-farm water supply" includes water from the U.S. Bureau of Reclamation; irrigation districts; mutual, cooperative, and other ditches; and reclaimed water from off-farm livestock facilities, municipal, industrial, and other sources.[25] Groundwater, on the other hand, is subsurface water that can be subdivided based on permeability, hydrological connectivity to surface waters, and other factors. Some groundwater is recharged by precipitation and runoff, including return flows from agricultural irrigation, and other groundwater is not readily replenished. Apart from connectivity, the use of surface and groundwater can be coordinated through conjunctive use projects that recharge groundwater via surface impoundments.

According to the USGS, U.S. farms applied 51.2 billion m^3 (41.5 million acre-feet) of groundwater from wells (49.8 percent), 10.2 billion m^3 (8.3 million acre-feet) of on-farm surface water (9.9 percent), and 41.4 billion m^3 (33.6 million acre-feet) of off-farm water (40.3 percent) to acres in the open in 2018.[26]

There are various costs associated with irrigation water from traditional sources. In 2018, 74,012 farms spent $1.1 billion for off-farm water, at an average cost of $0.03 per m^3 ($42.37 per acre-foot). However, the off-farm cost varied considerably from state to state, ranging from $0.01 per m^3 ($8.64/acre-foot) in Wyoming to $2.94 per m^3 ($3,625/acre-foot) in Rhode Island.[27] Of particular interest, in 2018, U.S. farms applied approximately 789 million m^3 (640,000 acre-feet) of "reclaimed wastewater" (as defined in the 2018 U.S. Department of Agriculture [USDA] Irrigation and Water Management Survey) from off-farm livestock facilities, municipal, industrial, and other sources.[28] In the same year, 158,236 farms spent $2.4 billion on energy for well and other irrigation pumps servicing more than 20.2 million hectares (50 million acres) in 2018, at an average cost of $91.40 per hectare ($37 per acre) for surface water and $118.60 per hectare ($48 per acre) for wells. However, 3,047 U.S. farms used solar pumps to irrigate more than 60,000 hectares (150,000 acres) with no direct energy expense.[29] Furthermore, 81,298 farms spent $2.0 billion on irrigation-related equipment, facilities, computer technology, and land improvements for more than 5.6 million hectares (14 million acres), at an average cost of $358 per hectare ($145 per acre).[30] Finally, 41,786 farms spent $1.1 billion on hired and contract irrigation labor for 9.87 million hectares (24.4 million acres), at an average cost of $113 per hectare ($46 per acre).[31]

The quality of irrigation water varies with location, based on geology, climate, seawater intrusion, human influences, and other factors, and it affects both soil properties (e.g., permeability) and crop health and safety. Good-quality irrigation water is generally colorless, odorless, and foamless with circumneutral pH, minimum turbidity, TDS below 1000 mg/L , and specific conductance below 150 millisiemens per centimeter (mS/cm).[32] The optimum salinity for many crops (e.g., alfalfa, almond, broccoli, celery, corn, cucumber, lettuce, orange, pepper, rice, tomato) is below two mS/cm, while some crops are more tolerant to salinity (e.g., four mS/cm for wheat and five mS/cm for barley, cotton, and wheatgrass).[33] Historically, salinity and dissolved solids have been the primary measure of irrigation water quality, but many other water constituents also affect crop health and safety. Elements such as As, B, Cl, and Se are toxic to plants in excess amounts, and they can accumulate in soils and be taken up by crops. Similarly, organic contaminants from human sources are now found in many traditional irrigation source waters[34],[35] and they too can accumulate in soils and be taken up by crops.

Common sources of agro-industry water include municipal water supplies and private wells. These sources take into account that the quality of this water is regulated by the Food Safety and Inspection Service of the USDA. Potable water is required for many purposes, and microbiological, chemical, and other contaminants are required to be reduced or eliminated to prevent adulteration of product.[36]

Traditional water sources set the standard for quality and economic feasibility when considering the agricultural use of nontraditional source waters at any location.

3.2.2. Nontraditional Sources: Municipal Wastewater

Wastewater treatment plants (WWTPs) in the United States process approximately 124.9 BLD (33 BGD) of wastewater.[37] After wastewater treatment, approximately 8.3 BLD (2.2 BGD) (7 percent, volume per volume [v/v]) is recovered, and a little over half of the recovered water (i.e., 4.7 BLD or 1.24 BGD) is reused for agricultural and urban irrigation (Figure 7). This comparison might make it seem as if there is tremendous potential for expanding the use of reclaimed water in agriculture[38] but much

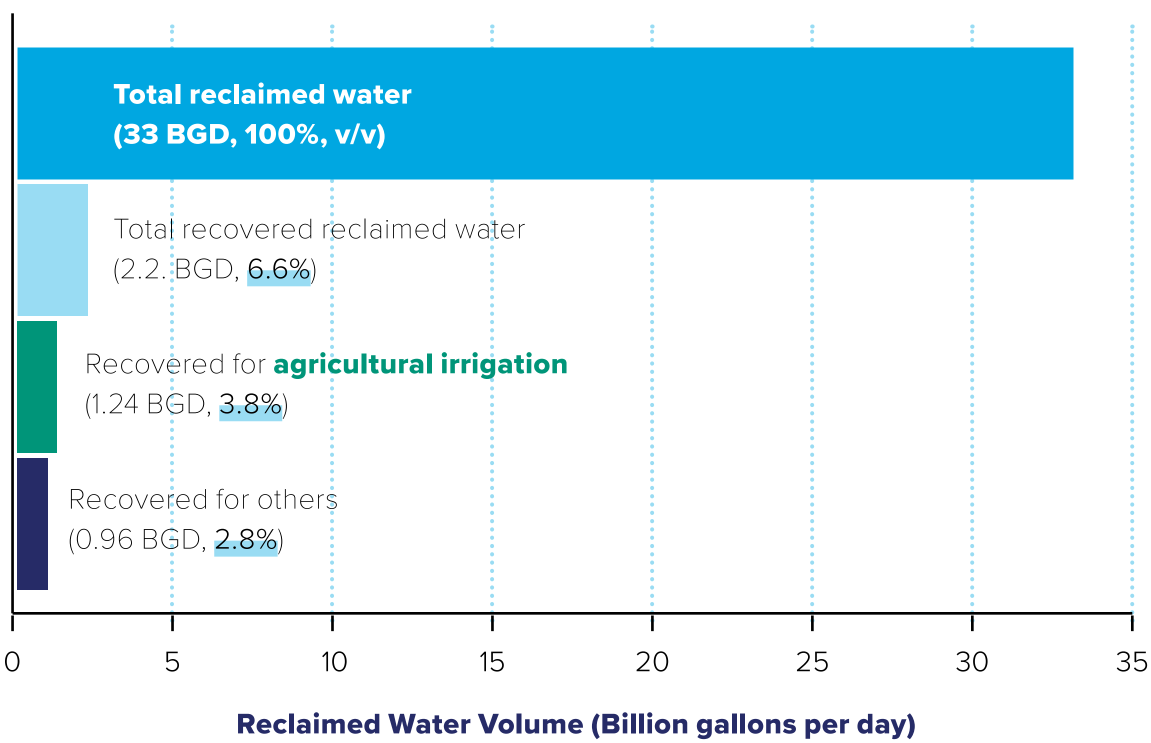


Figure 7. Estimated daily volumes of reclaimed water in the United States
Data obtained from WEF, Baseline Data to Establish The Current Amount of Resource Recovery from WRRFs, WSEC-2018-TR-003. 2018.

of the wastewater is generated far from where it is needed for agricultural purposes. The cost of constructing distribution systems to move treated wastewater from sewage treatment plants, which are often located near the center of metropolitan areas, to farms, which are often located outside of the most distant suburbs, makes it impractical for much of this wastewater to be reused for agricultural purposes. Nonetheless, there are ample opportunities for reuse in communities where potential users of recycled water are located close to its source.[39]

The types and concentrations of water quality constituents in reclaimed (or recycled) water depend on the influent characteristics (i.e., domestic and industrial contributions), the amount and composition of infiltration in the wastewater collection system, the treatment processes, and the type of storage facilities. Effluent quality from conventional WWTPs often poses technical challenges to agricultural irrigation due to the high levels of residual organic contaminants, salinity, and microorganisms.[40]

Conventional (biological) WWTPs can effectively remove significant amounts of biodegradable organic matter and ammonia N and achieve some degree of disinfection. However, conventional plants have not been specifically designed 1) to remove toxic CECs including pharmaceuticals, personal care products (PPCPs), endocrine-disrupting chemicals (EDCs), perfluoroalkyl and polyfluoroalkyl substances (PFAS), microplastics, and certain pathogenic microbes[41,42,43,44] and 2) to recover valuable nutrients such as N and P.[45]

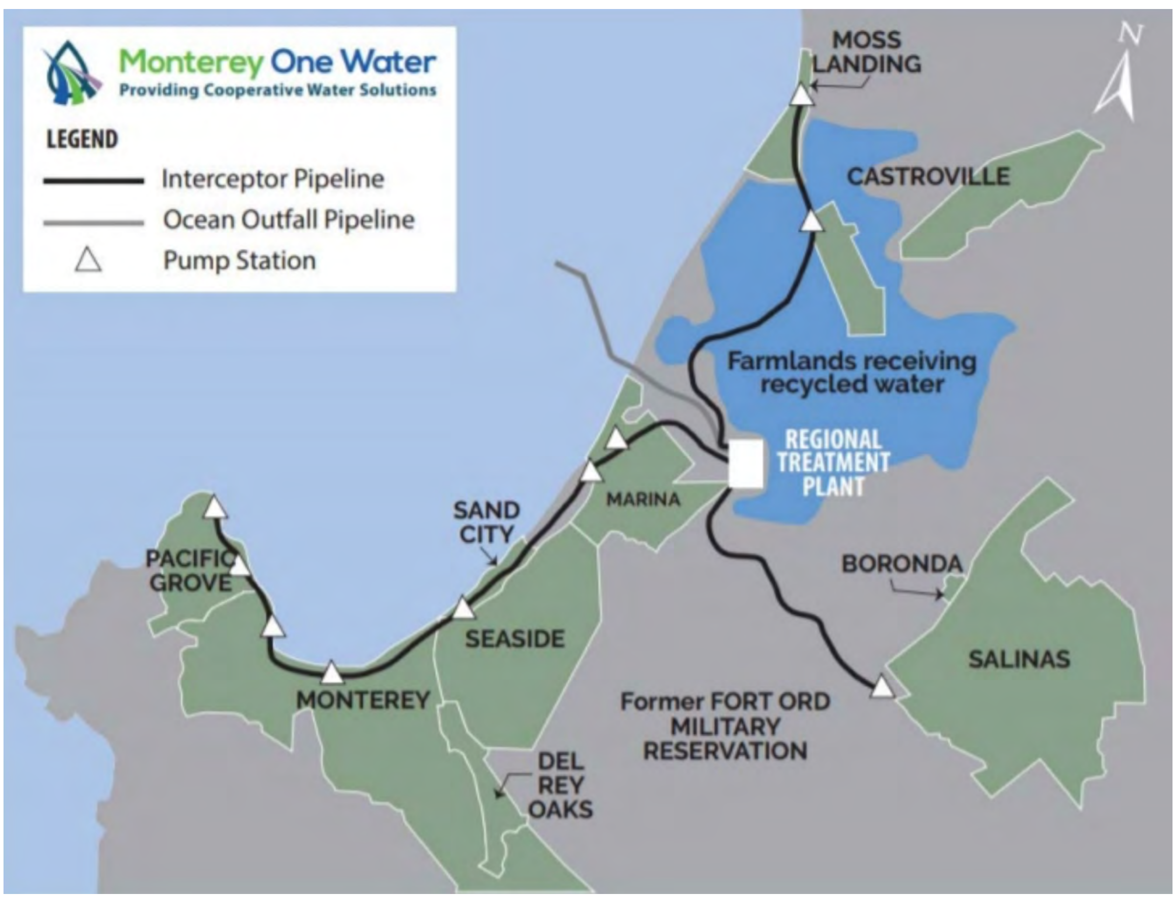


Figure 8. The project area of the Monterey County Water Recycling Projects (Monterey One Water), California[51]

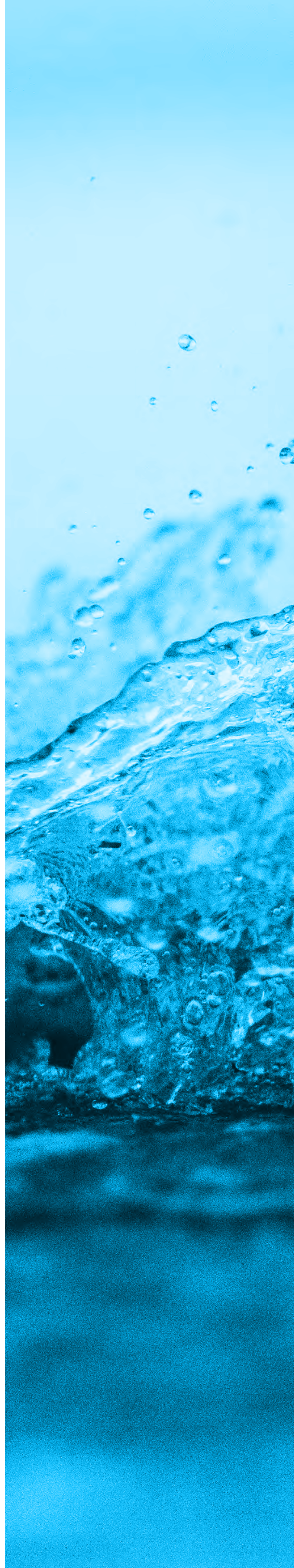
The reuse of treated municipal wastewater (TMWW) for irrigation is not a new concept and has been conducted safely for decades in water-scarce regions such as the Salinas Valley in California or Israel.[46,47] For example, the most recent recycled water survey identified that 18.4 percent of the TMWW (i.e., 2.5 BLD or 0.66 BGD) is reused in California, with approximately 69 percent used for non-agricultural purposes (e.g., landscape irrigation, groundwater recharge, golf course irrigation, and industrial use) and the rest of the recycled water (31 percent) for agricultural activities.[48] In the Central Coast area near Monterey Bay, Monterey County Water Recycling Projects (Monterey One Water), which combine the Castroville Seawater Intrusion Project (CSIP) and the Salinas Valley Reclamation Project (SVRP), began construction in 1995 and started delivering recycled water to fields near Castroville in 1998 (Figure 8). The tertiary treatment facility utilizes a three-step chemical and filtration process (i.e., coagulation/flocculation, multi-media filtration, and chlorine disinfection) to further treat secondary effluent.[49] Groundwater recharge is used to block seawater intrusion by using injection wells while treated wastewater irrigates high-value vegetable and fruit crops, reducing the demand for local groundwater. This project could provide up to 114 MLD (~30 MGD) for crop irrigation under drought conditions.[50] This multi-pronged approach benefits both farmers and cities. The treated wastewater sold to the agriculture community is subsidized to benefit overall improved groundwater conditions and support a robust agricultural economy, a net benefit to the region.

Discharges from WWTPs to receiving waters are required to meet federal and state effluent discharge limits outlined in the National Pollutant Discharge Elimination System (NPDES) permits, which include technology-based and receiving water quality-based limitations.[51],[52] These typically include limits for biological oxygen demand (BOD), TSS, N, P, dissolved oxygen, and fecal coliform bacteria.[53] However, these limits are often not stringent enough for the direct reuse of wastewater for agricultural operations.[54,55,56,57,58]

Despite the consistent reuse TMWW for irrigation in some arid regions, there are risks associated with the above-mentioned CECs and their persistence in WWTP effluent[59] because uptake of organic compounds from this effluent has been demonstrated in a wide variety of crops.[59,60,61,62,63] In some cases, plant accumulation of CECs is associated with human consumption and excretion of these compounds[64] and can reach concentrations in the edible parts that could be a potential health risk for vulnerable groups such as children.[65] Overall, when considering the unknowns associated with CEC toxicity, the likelihood of new compounds emerging, and our minimal understanding of plant uptake/metabolism, the prudent approach to reusing municipal wastewater for irrigation is consistent monitoring of water quality through thorough chemical characterization or tiered toxicological assessments.[66]

3.2.3. Nontraditional Sources: Brackish Water

Brackish groundwater (BGW) is widely distributed in nearly every state. The distribution of BGW (1,000 mg/L of TDS) can be classified into 10 regions: Coastal Plains, Eastern Midcontinent, Southwestern Basins, Western Midcontinent, Eastern Mountains and Uplands, Northwestern Volcanics, Western Mountain Ranges, Alaska, Hawaii, and U.S. Territories. The first four regions contain the massive volumes of BGW. Brackish water is mostly present in the Central United States that extends from Montana and North Dakota in the north to Texas and Louisiana in the south.[67]



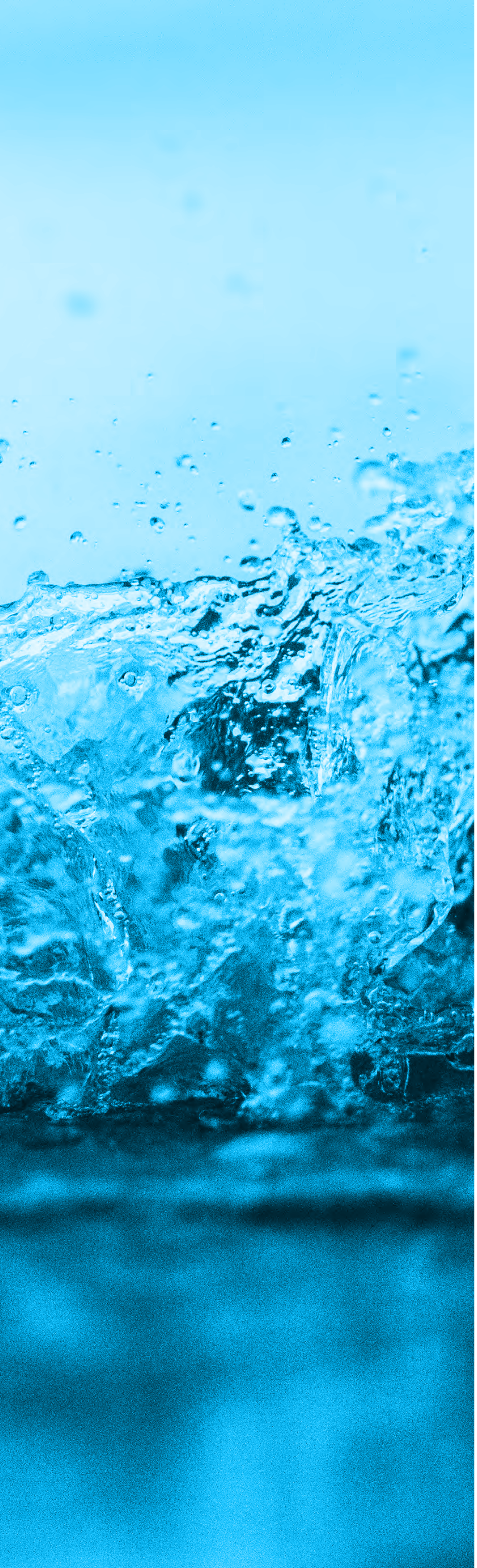
According to a USGS assessment, 20 percent of all groundwater in the United States is considered brackish water with TDS levels ranging from 1,000 to 10,000 mg/L, and about two percent was denoted as highly saline groundwater with TDS>10,000 mg/L. The groundwater salinity typically increases with the aquifer depth in BGW regions. For example, groundwater salinity increases from being slightly saline with TDS of 1,000 to 3,000 mg/L at 152 meters (500 ft) below land surface, to more saline with TDS of 3,000 to 10,000 mg/L by 457 meters (1,500 ft) below land surface, and to exceeding 10,000 mg/L by 914 meters (3,000 ft) below land surface.

The USGS estimated about 196 trillion m^3 (159 billion acre-feet) of observed grid cell volume contained BGW at depths between 152.4 m and 914.4 m (500 and 3,000 ft) below land surface. Groundwater modeling predicted that the volume containing BGW might be 14 times larger (i.e.,2.47 quadrillion m^3 (2 trillion acre-ft) than the observed data. However, the actual volume of usable BGW is uncertain due to a lack of information about the subsurface materials in these observed areas.[68]

Brackish water remains a substantial and largely untapped water resource for agricultural use. Water quality for irrigation depends on the types of crops and soil quality. Factors that affect crops negatively include salinity, sodicity (i.e., amount of Na^+ in irrigation water), and the specific ions' toxicity. The use of brackish water with salinity above 3,000 mg/L may become more restrictive due to the adverse impact on crop yield. Every crop has a salinity threshold after which yield declines, and the choice of crops that can be grown with brackish water declines with increasing soil or water salinity. In addition, high sodicity causes clay particles in soils to swell, clogging soil pores and reducing permeability, which in turn limits plant-available water, drainage, and plant growth. As a consequence, it is essential to manage the ratio of Na^+ to Ca^{2+} and Mg^{2+} in soils (i.e., SAR) to sustain healthy soil structure and maintain permeability.

Some shallower brackish groundwater aquifers could be contaminated by various organic and inorganic contaminants such as petroleum products, fuels, pesticides, chlorinated and fluorinated substances (e.g., trichloroethylene [TCE], PFAS), and other chemical substances due to human activity. These contaminants could accumulate in crops, fruits, vegetables, animals, milk, and other agricultural products and need to be removed before the water is used for agricultural purposes to protect public health.

Because crops vary in their tolerance to total salinity and toxicity of specific ions, and soil type influences the effect of sodicity on soil structure and permeability, treatment technologies would have to meet different water quality standards for different crops and soils. Point-of-use water treatment may be required to make use of brackish water for higher-value crops with low tolerance to salinity or certain ions. The selection of a suitable desalination technology for agricultural use depends upon the type of crops and their water quality requirement. Partial removal of salts and selective separation of certain constituents, such as removing harmful contaminants (e.g., Na^+, Cl-, B, metals, As, naturally occurring



radioactive materials [NORM], and organic contaminants), but retaining beneficial ions (e.g., K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, NO_3^-, and PO_4^{3-}) in the treated water, could reduce the treatment costs and provide nutrients for agricultural uses. Desalination facilities used for agriculture are comparatively small and, according to "economy of scale" principles, they produce water at a higher cost than large, centralized desalination plants. In addition, inland brackish water is more often associated with a finite groundwater aquifer, which requires a clear understanding of a sustainable groundwater yield to avoid aquifer depletion and degradation of groundwater quality.

The primary methods for brackish water desalination include reverse osmosis (RO), nanofiltration (NF), and electrodialysis reversal (EDR). RO separates almost all the organic and inorganic constituents in water, while NF can separate divalent ions, such as Ca^{2+} and Mg^{2+}, as well as organic compounds. For irrigation, this means that the SAR is not balanced in desalinated water, resulting in reduced soil permeability due to Na^+ and Ca^{2+} exchange. It often demands the addition of hardness to the desalinated water or the blending of the permeate with brackish water to meet the salinity and SAR requirements. On the other hand, desalinating brackish water to drinking water quality provides an opportunity to modify the water composition for fit-for-purpose uses. For example, some berry growers in California would like the brackish water to be treated to very low levels of salts so they can add in their preferred profile of nutrients in the irrigation water for high-value fruit crops.

Electrodialysis (ED) is an electrical-driven membrane desalination process suitable for partial desalination of brackish water; this process can work at high rates with high water recovery, making it viable for agricultural applications. Selective electrodialysis (SED) uses monovalent permselective membranes to selectively remove Na^+ and Cl^- ions while preserving most of the hardness and sulfate ions in product water as fertilizer for plant growth.[69,70,71,72] The selection of desalination technologies for agricultural uses should consider the capital, energy and membrane replacement costs, savings in feedwater costs from operating at higher recovery, and potential savings in fertilizer from using selective desalination technologies.

The wider application of desalination technologies for agriculture is limited by the high costs associated with its energy consumption and brine disposal. Membrane fouling and scaling remain a challenge for brackish water desalination. Dynamics of feedwater characteristics (e.g., TDS, sparingly soluble salts, pH, water temperature, variability of water quality) must be considered when designing a brackish water desalination system. For example, the groundwater from volcanic aquifers of the Southwestern United States and unconsolidated aquifers in the northern Great Plains is rich in barite. Barite scaling is a costly problem for membrane desalination processes, resulting in flux decline and membrane damage. Silica, calcium carbonate, calcium sulfate, and iron oxides can also precipitate when water recovery increases, causing membrane scaling. Biofouling is another possible challenge if the brackish water contains nutrients and organic matter. Therefore, adequate pretreatment should be applied for membrane fouling and scaling control.

The selection of brine disposal methods represents a compromise between technology availability, total cost, local resources, and environmental impacts. Disposal options may include discharge to oceans, rivers, lakes, lagoons, wetlands, evaporation ponds, deep wells, land applications, and sewer systems. Surface water discharge will likely be the most common management practice, as it is the least expensive option among other available brine disposals. However, depending upon water recovery and concentration factors, this may change the salinity of the receiving water, thereby changing the water chemistry (e.g., dissolved gases and lack of oxygen) and affecting aquatic life. If the feed of brackish water desalination is groundwater, the concentrate brine may require treatment before disposal because it typically contains high concentrations of gases, such as carbon dioxide (CO_2), ammonia, and hydrogen sulfide (H_2S). These dissolved gases are harmful and toxic to aquatic life. If the concentrate salinity of the brackish water desalination facility is not too high, or the concentrate can be blended with other water sources, the concentrate may be suitable for irrigating some salt-tolerant crops.

The removal of small, neutral solutes such as B by membrane processes is highly affected by their charge; neutral boric acid dominates in waters with pH values below 9.[73] Depending on the brackish water quality, pH, and temperature, and feed B concentration, a high rejection RO membrane or a second-pass RO may be used to produce the irrigation water with B concentration below 0.5 mg/L. Caustic soda addition may be needed to raise pH around 9.5 to increase B rejection. However, caution must be taken to avoid precipitative scaling by other constituents such as Ca^{2+}. Depending on the B concentration required for irrigation, another option is to use selective B ion exchange resin. The selective resin needs to be regenerated on site with caustic soda and hydrochloric acid.

3.2.4. Nontraditional Sources: Oil and Gas Produced Water

The use of produced water (PW) from oil and gas (O&G) extraction for agriculture faces many of the same challenges as those described for brackish water, as PW generated from O&G extraction is highly saline, with salinity equal to or higher than brackish waters. As a result, water quality concerns and treatment needs are similar, especially for low-salinity produced waters (<10,000 mg/L TDS). However, produced waters often present greater challenges for reuse due to higher salinities that require greater treatment, lead to residual salt generation, and give rise to concerns associated with bulk and trace organics.

The volumes and quality of PW from O&G extraction vary widely across the United States. Major plays include the Permian, Marcellus, Niobrara, Eagle Ford, Marcellus, Bakken, Barnett, Haynesville, Anadarko-Woodford, and Utica. In total, the United States generates approximately 3.88 trillion liters (24.4 billion barrels) of PW yearly.[74] However, PW is not equally distributed among oil plays, and regional variation in the supply and demand for PW within the O&G industry complicates the reuse, recycle, and disposal of PW.[75,76,77] Of PW generated in the United States, 91.5 percent is injected into the subsurface for either enhanced oil recovery or into non-commercial disposal wells, 5.5 percent is discharged to surface water, and 1.3 percent is utilized for beneficial reuse outside of the O&G industry.[78]

Water quality also differs spatially and temporally across O&G plays. PW may contain a host of contaminants—including inorganics, organics, radionuclides, microorganisms, and dissolved gases—that may complicate treatment, reuse, and residuals management.[79] The profile of inorganic constituents in PW can vary widely between formations and even between wells within the same formation.[80,81] Of particular note, the TDS or salinity varies tremendously (from approximately 100 to 400,000 mg/L), which has a major impact on potential reuse options.[82] While TDS may limit potential feasible and cost-effective reuse options, other inorganic constituents, like B and heavy metals, may be present in concentrations that are detrimental to plant and soil health and, consequently, may require additional treatment.[83] Similarly, PW often contains a plethora of organics that vary with both the composition of residual hydrocarbons and the production chemicals utilized during extraction. For example, a thorough analysis of PW from 8 wells within the Midland Basin indicated the presence of approximately 1,400 organic chemicals.[84] Ultimately, the wide variation of PW quality highlights the need for characterization and treatment approaches for PW to ensure sustainable beneficial reuse.

While there has been interest in using PW for irrigation, the wide variability of water quality and quantity of PW may limit the applicability and feasibility to a limited number of locations. Produced water volumes vary throughout the life cycle of a well, and, in turn, across a basin. These time frames depend on a number of factors including formation characteristics and market economics. Irrigation of even non-food crops requires relatively high-quality water and transportation costs may require co-location of production and end-use sites. As a result, the decision to use PW for irrigation will likely occur on a case-by-case basis.

PW is often distinguished based 1) on the type of extraction (e.g., conventional PW referring to vertical well operations or unconventional PW referring to horizontal fracking operations) and 2) by the make-up of the water that returns to the surface (e.g., flowback water [the water used to induce fracking], or PW [the naturally occurring formation water]). The use of produced water for irrigation is highly dependent on the overall salinity, bulk composition (e.g., hydrocarbons, salts), and trace chemicals of concern (e.g., metals, fracking additives, NORM). Some unconventional PW organics are poorly characterized and/or may lack information on toxicity, fate, and transport.[85] Traditionally, bulk organics in conventional PW may also limit both plant health and growth.[86,87] Pica et al. recommended a TOC concentration of less than five mg/L to sustain biomass production rates.[88]

A number of specific concerns regarding the level of treatment required and the uncertainty associated with PW's impacts on soil health must be resolved prior to widespread use of this resource for agriculture.[89]

Low-salinity PW, with TDS ranging from 200–2,000 mg/L, minimal organic constituents (e.g., residual hydrocarbons), and trace concentrations of chemicals of concern (e.g., B, Se) would require minimal treatment and may be suitable for long-term irrigation. For example, low-salinity PW has been used for irrigation in parts of Southern California.[90] Farmers have used blended PW to irrigate almonds, citrus, and a variety of vegetable crops. The treatment train for the PW focuses on oil removal, followed by blending the PW with higher-quality water. The PW first undergoes mechanical separation, followed by sedimentation, air flotation, and finally filtration through walnut shell filters.[91] Once the oil is removed, some water is diverted for steam generation or lease water, but the majority is pumped to a series of reservoirs for blending and eventually discharge to the agricultural irrigation systems.[92]

On the other hand, high-salinity PW, with TDS ranging from 10,000–400,000 mg/L, would require a much more intensive and expensive process focused exclusively on TDS removal to meet agricultural standards. Limited studies have addressed the long-term impact on soil health of using highly saline PW for irrigation.[93] In addition, the limited studies addressing issues of soil health of PW irrigation heavily rely on gypsum to achieve acceptable SARs. There is limited information regarding toxicity (especially synergistic effects), fate, and transport, as well as limited regulatory health thresholds for many organic chemicals in PW.[94,95] Further, many of the constituents and, when applicable, their transformation products present in the PW, may go undetected due to the traditional analytical methods employed or because their concentrations are below instrument detection limits.[96] Inadequate characterization of contaminants present in PW may result in the introduction of new or poorly characterized exposure pathways that could pose risks to either ecological or human health.[97]

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3.3. Water Discharged from Agriculture

3.3.1. Agricultural Drainage Water

Agricultural water discharges can include excess water from precipitation events. Crop yields are reduced when soils are saturated for extended periods because soil aeration is necessary to promote root development and nutrient uptake.[98] As a result, artificial surface or subsurface (e.g., tile) drainage is commonly used to improve soil aeration, field stability, and nitrification in soil, resulting in more nitrate available for plant uptake.[99] Surface drainage typically consists of a series of ditches that run along the edges of farmland, and tile drainage consists of high-density polyethylene (HDPE), polyvinyl chloride (PVC), concrete, or clay pipes that are buried below croplands and direct water away from plant roots to a ditch, reservoir, evaporation pond, or surface water.

According to the 2017 Census of Agriculture, 218,165 U.S. farms used tile drainage for 22.5 million hectares (55.6 million acres), and 212,394 farms used artificial surface drainage for 17.8 million hectares (43.9 million acres).[100] The top five states in acres drained by tile or artificial surface ditches were:

STATE	ACRES DRAINED BY TILE
Iowa	**14.1** million
Illinois	**9.5** million
Minnesota	**8.1** million
Indiana	**6.4** million
Ohio	**5.4** million

STATE	ACRES ARTIFICIALLY DRAINED BY DITCHES
Minnesota	**4.7** million
Illinois	**3.6** million
North Dakota	**3.4** million
Arkansas	**3.1** million
Louisiana	**2.7** million

Because irrigation and precipitation vary with time and place, the need for drainage also varies by region. In 2017, the 17 Western States accounted for 6.8 percent of the acres drained by tile and 28.9 percent of the acres artificially drained by ditches, even though they accounted for 46.1 percent of the harvested cropland and more than 80 percent of the irrigation volume.

Agricultural drainage often contains nitrates, phosphates, salts, and other soluble chemicals, and it has been associated with surface water eutrophication and increased salinity in surface and groundwater.[101,102] Agricultural storm water discharges and return flows from irrigated agriculture are not considered "point sources" under the U.S. Clean Water Act,[103] so the regulation of nutrients and other constituents of agricultural drainage is primarily governed by state law.[104] Most states require written nutrient management plans, and some states have application restrictions or education programs.[105]

Increasing salinity poses a special problem in poorly drained fields and watersheds. In California's San Joaquin Valley, which produces more than half of the state's agricultural output, salt buildup in soils and groundwater is threatening the agricultural region's productivity and sustainability.[106] In fact, agricultural drainage in the San Joaquin Valley can have a range of TDS concentrations (5,000–20,000 mg/L),[107] and a 2017 remote sensing study described more than 386,000 hectares (955,000 acres) in the San Joaquin Valley as moderately to extremely saline.[108] The potential economic impact to the region of this growing salinity problem has been estimated to exceed $3 billion per year.[109]

3.3.2. Meat and Dairy Processing Wastewater

Agricultural source waters, like meat and dairy processing wastewater, require extensive treatment before discharge under NPDES permits. Meat processing wastewaters include TSS, oil and grease, chemical oxygen demand (COD), BOD, P, and N.[110] Beef processing, including hide treatment, is the most complex of meat and dairy processing wastewaters.

In general, the treatment train for beef processing wastewater is comparable to municipal wastewater treatment and includes preliminary, primary, secondary, and tertiary treatment. The purpose of the pretreatment step (i.e., screening) is to separate the high levels of suspended solids and organics from the wastewater. After pretreatment, the effluent undergoes primary and secondary treatment to reduce oil and grease, TSS, and BOD levels. The most commonly used primary and secondary treatment technologies are dissolved air flotation (DAF) and anaerobic digestion followed by disinfection. After secondary treatment, depending on the levels of TDS, the addition of another treatment step (e.g., RO) may be implemented to remove additional salts from the wastewater.

The initial stages of hide processing include brining, which is water- and, more importantly, salt-intensive. Brining requires a 25–40 percent concentration of salt (TDS levels of 350,000–400,000 mg/L).[111] Of this salt, only a very small amount is absorbed into the hides, leaving up to 16.6 liters (4.4 gallons) per hide of very highly concentrated brine as wastewater. Although the volume of wastewater from brining is low, the ultra-high concentrations of salts still contribute to 64 percent of the total TDS loads from the beef processing plant wastewaters (Table 1).

	TOTAL PLANT WASTEWATER QUALITY (POINT 1)	HIDE BRINING WASTEWATER QUALITY (POINT 2)
	WASTEWATER FLOWRATE: 1,875 GPM	WASTEWATER FLOWRATE: 18 GPM
CONSTITUENT	CONCENTRATION (MG/L)	CONCENTRATION (MG/L)
Chemical Oxygen Demand	**6,050**	**20,180-22,160**
Biological Oxygen Demand	**2,800**	**7,605-8,430**
Total Kjeldahl Nitrogen	**228**	**938.5-958.1**
Total Suspended Solids	**1,220**	**5,667-10,333**
Chloride	**290**	**145,400-166,600**
Sodium	**1,060**	**75,000-99,000**
Total Dissolved Solids	**1,350**	**Above 250,000**

Table 1. Representative wastewater segregated by total plant and concentrated high salinity wastewater in a beef processing plant
(Industry provided data)

Figure 9, below, shows the water flow through a beef processing facility. Three main options of hide brining wastewater management are practiced within industry. The first option is to dilute the brine in other plant wastewaters, in the hope that salinity limits are low enough for discharge under NPDES permits after treatment. If those limits are not reached, additional clean water may be added to dilute the water further. The second option involves releasing the brine to evaporation ponds, where salts are left to solidify as water is evaporated to the atmosphere. After evaporation, the cleanup of dry salts and organics can be costly. The third option is deep well injection of the hide brining wastewater, with costs similar to the cost of injecting produced water ($0.01 per liter to $0.02 per liter [$0.02/gal to $0.07/gal]).

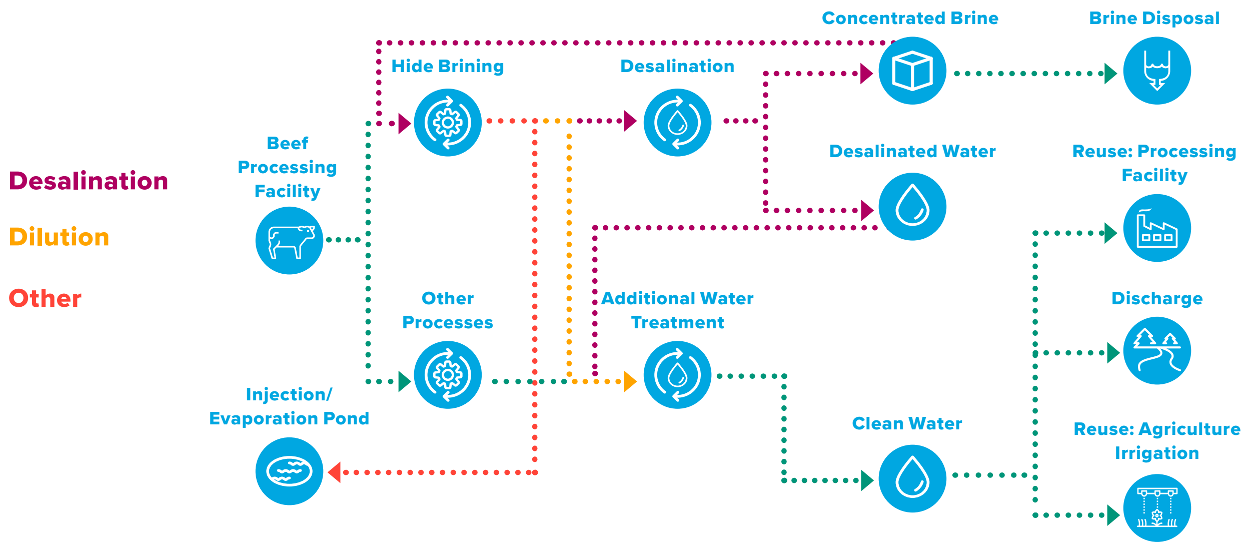


Figure 9. Wastewater treatment and reuse options in a beef processing facility

Desalination is another option being explored in industry because it allows for the most reuse within and outside of the processing facility. Concentrated brine produced from the desalination process can be reused within the hide brining process, displacing new salt costs. Additionally, the desalinated water can be treated with the rest of wastewaters from the processing facility without compromising reuse opportunities due to high TDS levels of the effluent water. Again, however, the costs associated with the desalination processes are high (around $0.02/liter [$0.07/gal]; Table 2). DOE reported that in 2016, industrial water could be attained from$0.0002/liter to $0.004/liter [$0.001/gallon to $0.017/gallon] for dilution, offering limited incentive to treat concentrated brine.

Desalination technologies used to treat brining wastewater are susceptible to fouling due to undigested oil and grease and dissolved proteins. Evaporative technologies, such as submerged combustion, are another alternative, but they require periodic cleaning and maintenance, which hinders the autonomy and resilience of the wastewater treatment system. Other alternative technologies, such as RO and forward osmosis (FO), are not able to operate at such high salinities and thus are not an option for desalination of hide brining wastewaters from meat processing.

Dairy processing also produces highly saline wastewater from certain processes. Brining of cheese is an isolated process with high wastewater salt concentrations ranging from 150,000 to 350,000 mg/L, depending on the type of cheese and brining duration.[112,113] The primary challenge with the treatment of cheese making wastewater is desalination, where TDS levels can range from 5,000 to more than 20,000 mg/L.[114] The available technologies are generally similar to the treatment of hide brining wastewater.

Wastewater Flowrate: 18 GPM

CAPITAL		OPERATIONAL (YEARLY)	
Evaporator	$ 1,200,00	Labor	$ 165,500
Coagulator	$150,000	Electrical	$42,000
Tanks/misc. equipment	$ 250,000	Steam Generation	$ 465,000
Install	$ 1,100,000	Repair/Maintenance	$ 90,000
Engineering/Design	$ 75,000	Salt Recovery	$ -312,000
Misc.	$ 650,000		**$ 450,000/year**
Total CAPEX:	**$ 3,425,000**	**Total OPEX:**	**$0.067/gallon**

Table 2. Cost of treating high-salinity wastewater in a beef processing facility
(Industry provided data)

3.4. Reuse of Water Discharged from Agriculture

3.4.1. Reuse of Drainage Water

In 2018, 4,829 farms reported using recycled water to irrigate more than 394,000 hectares (974,000 acres).[115] Irrigation using treated agricultural drainage can provide supplementary water and reduce the impact of nutrients and other drainage constituents on the environment. According to the National Water Reuse Action Plan, there are approximately 170 BLD (45 BGD) of agricultural return flows from irrigation,[116] which can contain up to 8 kg N fertilizer per hectare per year (3.24 kg N fertilizer per acre per year).[117]

In many regions, drainage constituents (inorganic fertilizers) are valuable products to the farmers, so the primary reuse system would be a “tailwater recovery system” that simply recycles the tile drainage upstream to irrigate the fields with the stored water as needed (Figure 10). For example, natural treatment technologies (e.g., constructed wetlands) are used to remove excess nutrients before reuse as irrigation or discharge to surface water. However, this treatment/reuse strategy may not be feasible in regions like California due to high salinity and the presence of toxic constituents (e.g., Se, As, B) in the tile drainage.

In California, the drainage water quality is not suitable for long-term reuse on crops without undergoing some type of treatment (Figure 10). Due to the high cost and energy consumption of advanced treatment processes like RO and solar desalination, these technologies are not widely used to treat agricultural drainage. California has a few demonstration/pilot treatment plants for management of selenium and desalination of agricultural drainage to test the feasibility of these technologies, but most technologies are still in the laboratory testing phase. For example, the San Luis Demonstration Treatment Plant (SLDTP), located in California's Central Valley, is a 1.1 MLD (288,000 gallons per day [GPD]) demonstration-scale desalination plant that was constructed in 2016 to manage selenium and salt in agricultural drainage. The SLDTP tests the feasibility of using biological treatment and desalination processes to remove Se and salts from the agricultural drainage. The treated water has not been used for irrigation as this plant was constructed to determine the optimal treatment train. In addition to advanced treatment, another saline drainage management strategy is sequential reuse, also known as integrated on-farm drainage management (IFDM). IFDM is the practice of reusing saline drainage water on increasingly salt-tolerant crops. With this reuse strategy, the volume of saline drainage is reduced and the remaining water is disposed to an evaporation basin.

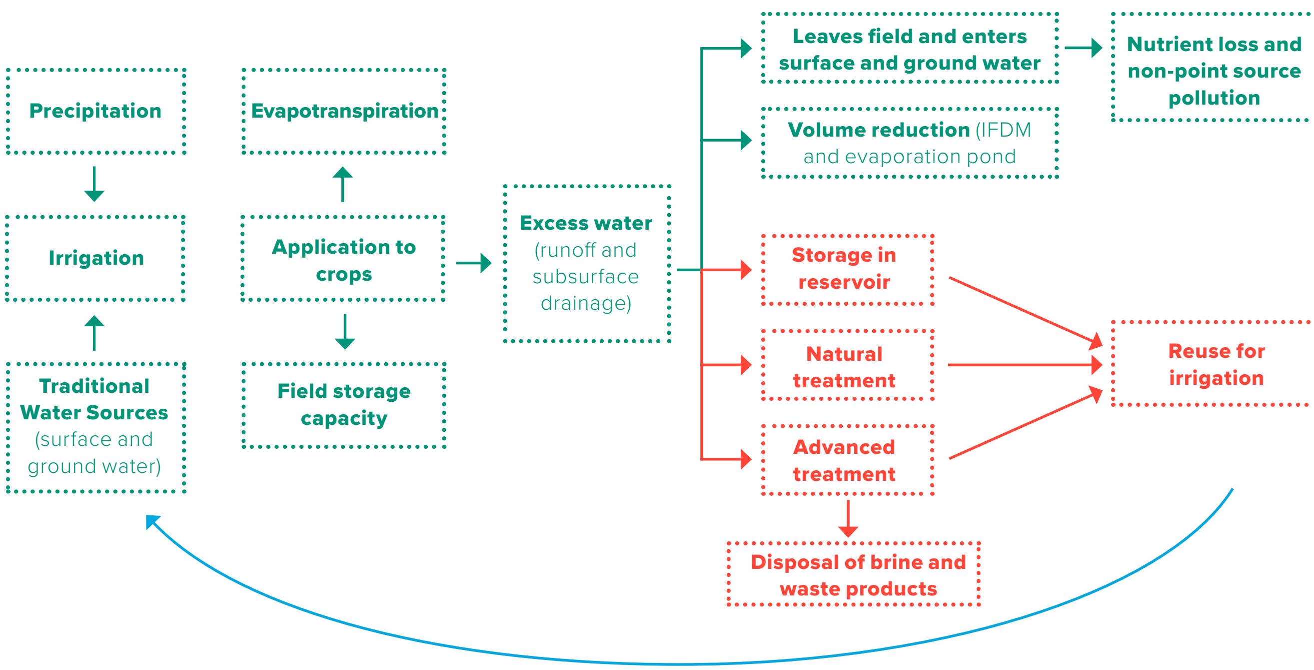


Figure 10. Current and potential pathways for agricultural drainage (green lines) and potential pathways (red lines) for drainage reuse for irrigation

3.4.2 Reuse of Meat and Dairy Processing Wastewater

Water reuse within meat and dairy processing plants is currently limited, though certain unit processes (e.g., pasteurization in meat processing) do recirculate water and exchange it for fresh water two to three times per day.[118] However, the USDA Food Safety and Inspection Service has encouraged the implementation of advanced technologies that allow for water reuse within the facility, as long as the procedures and safety measures are clearly addressed in the facility's Hazard Analysis Critical Control Point (HACCP) plan, Sanitation Standard Operating Procedure (SSOP), or another required program.[119] The potential for wastewater reuse in meat and dairy processing plants is well illustrated by the Harmony Beef plant in Alberta, Canada, which reuses 90 percent of its water within the processing facility.[120] However, this plant is a state-of-the-art small-scale facility that is operated under extensive sustainability practices and is not optimized for cost. The potential for reuse of meat processing wastewater in large-scale U.S. production facilities is currently constrained by cost, regulations, and public attitudes about wastewater reuse in food production.

Because meat and dairy processing plants are commonly located in agricultural areas, the reuse of wastewater for agricultural irrigation is also possible. In fact, numerous studies have reported the benefits that can arise from using meat processing wastewaters for irrigation.[121] A further consideration of cheese processing is that it is a significant water producer, meaning that there would be a constant need for the discharge or reuse of excess wastewaters in other applications, such as agricultural irrigation, even if water is also treated for reuse within the facility (Figure 11).

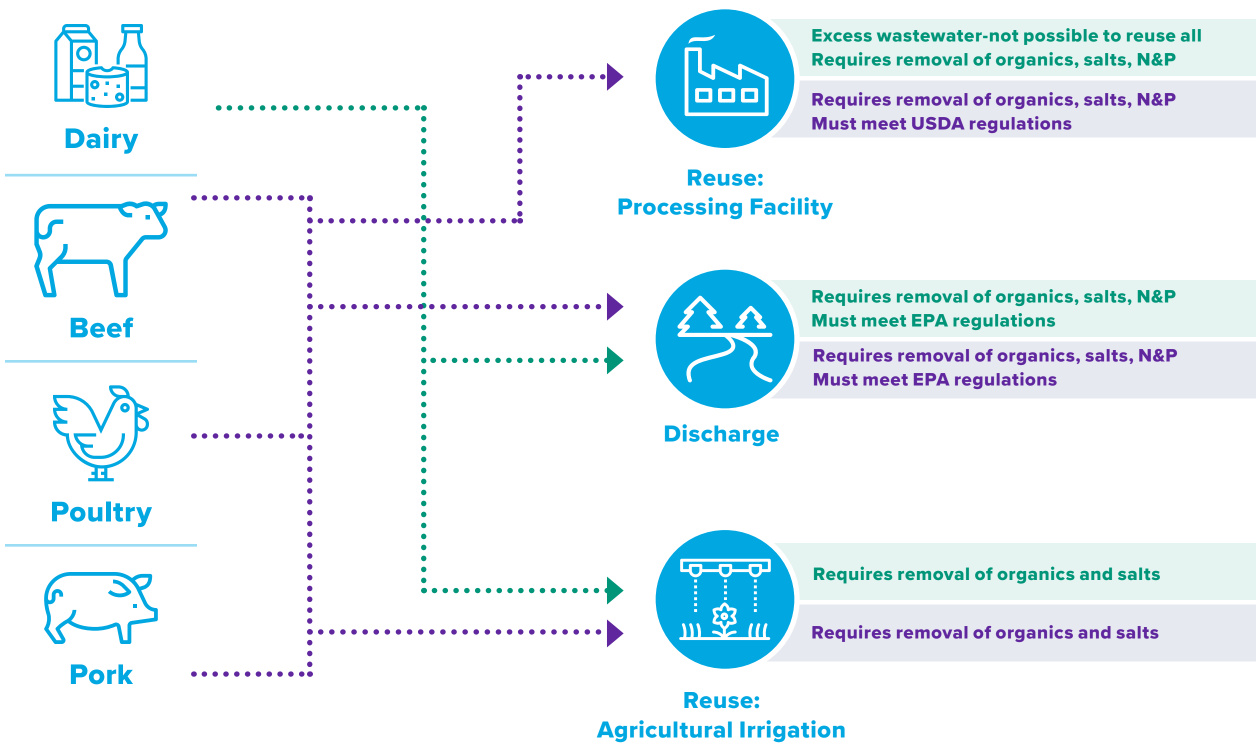


Figure 11. Flow of treated wastewater from meat and dairy processing facilities

3.5. Resource Recovery

Agricultural drainage can contain a range of different salts, with sodium sulfate and sodium chloride being some of the more common species.[122] To offset the cost associated with the disposal of brine from the treatment of saline agricultural drainage, the usable salts can be reclaimed, reused in agricultural activities, or sold to other industries. A recent study on recovering salts from agricultural drainage in California estimated that the recovered sodium chloride and sodium sulfate could have a value of about $35 per metric ton and $140 per metric ton, respectively.[123]

The following situations are examples of how valuable resources can be recovered from agricultural drainage and reused. Through electrochemical processes, purified sodium sulfate from agricultural drainage can be used to make sodium hydroxide and sulfuric acid.[84] Sodium chloride recovered from the treatment of waste brine can be reused in the treatment processes or can be sold to other industries to use for road de-icing.[124] Agricultural drainage also contains calcium sulfate that can be recovered and used within the agricultural industry. A major challenge in implementation has been the expenses associated with recovering, transforming, and transporting the valuable materials to an appropriate market.

In meat processing, constituents removed from wastewater provide multiple opportunities for valorization. Valorization within the meat processing industry can reduce costs associated with transportation and lower environmental impacts. As a first example, salts recovered from the desalination of hide brining wastewater can be reused in new hide brining processes, as they do not have to meet food-grade quality standards. Similarly, biofuels produced in flotation can be used to replace natural gas in the plant for heating water before processing. A beef processing plant consumes 423 and 1113 megajoules per metric ton (MJ/ton) (384 and 1,010 MJ/ton) Live Weight (LW) of electricity and natural gas, respectively. The high rates of electrical energy and natural gas consumption are associated with the refrigeration and freezing of produced meat and with the heating of water for meat processing.[125] A combination of waste heat from plant operations and biofuels produced in the treatment of wastewater could improve the economic viability of different treatment options.

Another valorization option is the recovery of N and P from the wastewater to be used in the productions of fertilizers. In conventional WWTPs (i.e., based on biological processes), sewage sludge is a major byproduct. The global production rate of dry sewage sludge is 60 million metric tons (66 million tons) per year with an annual production rate of 20–40 kg per capita.[126] Typically, sewage sludge contains recyclable and agronomical valuable macro- and micro-nutrients.[127]However, it also includes several harmful organic and inorganic pollutants such as heavy metals (e.g., cadmium [Cd], chromium [Cr], copper [Cu], lead [Pb], manganese [Mn], and zinc [Zn]), pathogens (e.g., bacteria, protozoa, and viruses), and persistent organic pollutants (e.g., polycyclic aromatic hydrocarbons [PAHs], polychlorinated biphenyls [PCBs], polychlorinated naphthalenes [PCNs], polycarbonate microplastics, organophosphate esters, PPCPs, EDCs, PFAS, and microplastics).[128,129,130,131,132,133,134]

The conversion of sewage sludge to energy (e.g., biofuels, methane, and hydrogen) and/or high-value byproducts (e.g., biofertilizers and glycerols) through biological pathways appears to be a promising and eco-friendly alternative compared to the existing physicochemical and thermal methods.[135,136,137,138] However, the major limitation to the biological conversion of sludge to energy and/or high-value byproducts at an industrial scale is the low productivity and the low yields of the conversion processes due to the complex constituents present in sewage sludge.[139,140,141]

3.6. Agriculture Sector Pipe Parity

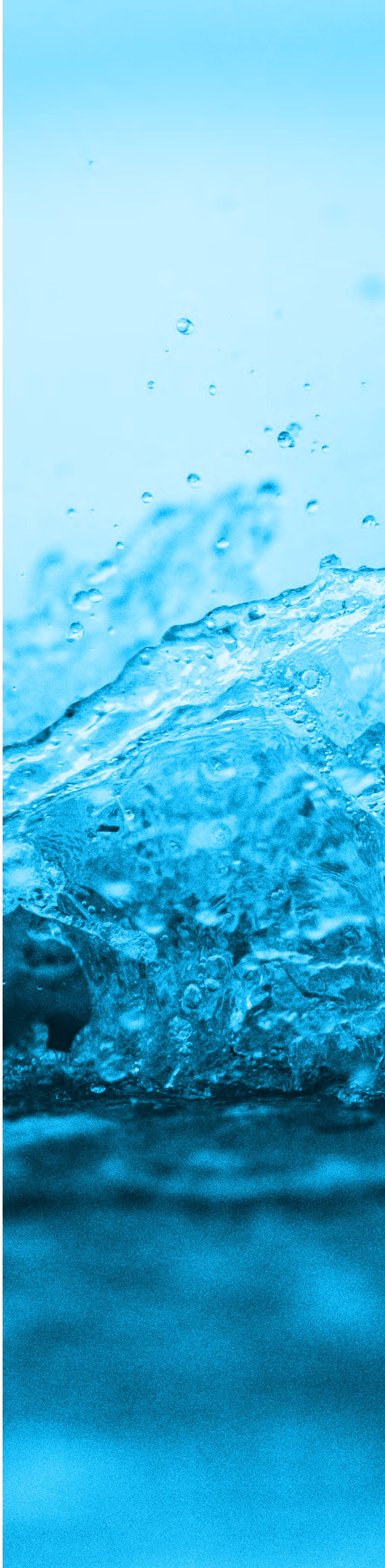
For the Agriculture Sector, reliably delivering high-quality water at an affordable cost to farmers and livestock ranchers is paramount. Therefore, cost (i.e., levelized cost of water [LCOW]) and reliability pipe-parity metrics will be critical when evaluating the potential use of nontraditional source waters in agricultural operations.

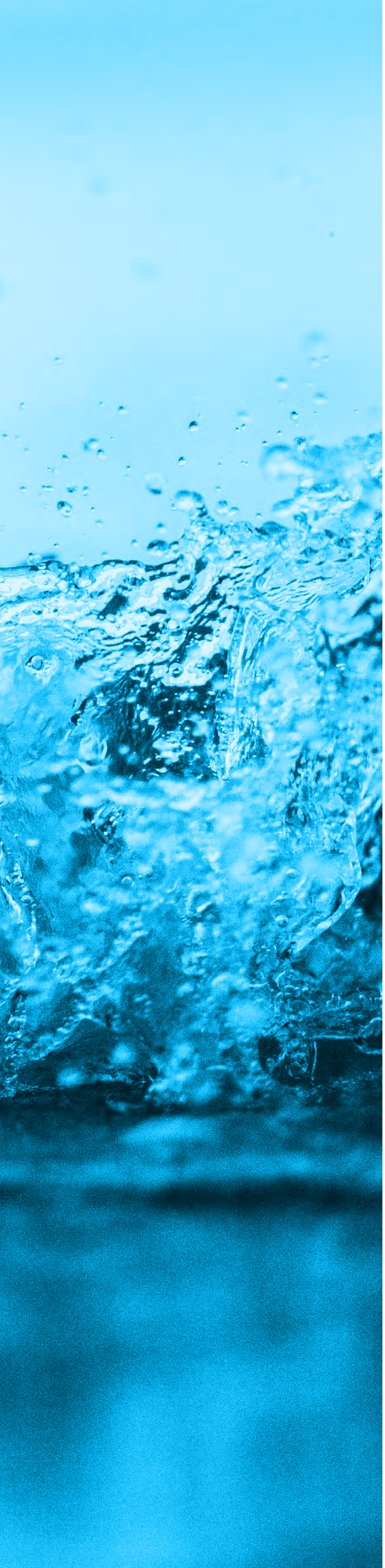
Pipe-parity metrics will vary regionally across the United States due to many factors, including heterogenous demand and variability in water quantity and quality, proximity, and accessibility to nontraditional water sources. In the existing water-stressed regions of the United States (e.g., Southern California, Arizona, Texas, and Florida), nontraditional source waters are already being utilized to supplement irrigation demand. For example, farmers in Southern California, have been using blended low-salinity PW for over two decades to irrigate almonds, citrus, and a variety of other crops (see Section 3.2.4.). In Texas, approximately three percent of the state's water supply is met by reusing municipal wastewater, though mainly for irrigating golf courses. In moderately or slightly water-stressed regions, a broader range of metrics is needed to assess the attractiveness of including nontraditional water supplies when persistent scarcity is not an issue. These include water quality, recovery of resources (e.g., water, salts, nutrients, and biofuels), environmental impacts (e.g., carbon footprint, greenhouse gas emissions, and eutrophication), conveyance (e.g., proximity and accessibility to supplies), agro-ecosystem impacts (e.g., crop and soil health), and societal impacts (i.e., public perception).

3.7. Water Laws

The ability to withdraw surface and groundwater and the ability to collect and reuse drainage water are subject to state water laws. These laws may be different for surface and groundwater, even though groundwater is often hydrologically connected to surface water.[142] The rules for surface water broadly follow two systems: 1) the riparian doctrine developed in the Eastern United States, and 2) the prior appropriation doctrine developed in the Western United States. However, a few states, including California and Oklahoma, have adopted a hybrid system that incorporates elements of both.

Under the riparian doctrine, a landowner with property adjacent to surface water can make reasonable use of the water, and non-use does not extinguish this right.[143] Under the prior appropriation





doctrine, the first person to "beneficially" use water from a water body has an absolute right to continue to use the same quantity of water for the same purpose,[144] but lack of use can result in abandonment.

In Colorado, a prior appropriation state, beneficial uses include irrigation, stock watering, municipal, power generation, oil and gas production, water storage, recreation, fish and wildlife culture, and many other purposes, and any new use is subject to the prior appropriation system.[145] Consumptive use defines the "measure and limit" of a water right,[146] and return flows generally belong back in the public's water source for appropriation and use. This might make agricultural reuse difficult without previously established storage rights or augmentation to replace the intercepted water. The prior appropriation doctrine is also applied to groundwater in many Western States. An exhaustive review of water law is beyond the scope of this document, but state water laws should be examined whenever reuse is considered, particularly in the Western states where irrigation water demand is greatest.

3.8. Toxicological Challenges

An important phase of evaluating nontraditional water for beneficial use is the analysis of the treated water's toxicity because beneficial reuse often corresponds to eventual human consumption. However, in an agricultural setting, the toxicity, of this water can also impact soil quality (both soil chemistry and microbiome) and plant health, including plant uptake and the accumulation of toxic constituents.[147,148,149,150] For example, research has shown that irrigating crops with diluted produced water (a proposed source for agricultural reuse) can result in lower crop yields, reduce soil microbial diversity, and make plants more susceptible to pathogens by suppressing the plant's immune system.[151,152] Comparable research has also shown similar effects in crops irrigated with treated municipal wastewater[153,154,155,156] (another proposed wastewater source). Consequently, effectively evaluating both acute and chronic toxicity of this treated wastewater will be a necessary process to avoid any detrimental impacts on the various natural systems that will be exposed to this water.[157]

Toxicological analysis is challenging when working with these wastewater sources for various reasons. First, acidic or highly saline water can have complex matrix effects that interfere with toxicological assays. Moreover, synergistic effects can be unique to each water source, limiting generalizability. In addition, not all constituents have toxicology that has been characterized, and long-term carcinogenetic effects can be difficult to predict.[158,159,160] The toxicity of endocrine disruptors is one example of the challenges these chemicals present. Zebrafish exposure and other bioassays have validity, but the analysis still presents a significant level of uncertainty.[161] The highly variant combinations of chemicals present in these wastewaters can present another challenge, but in silico modeling can be a useful tool to predict toxic synergistic effects that can then be selectively analyzed in vitro. Although this field is in its infancy, some research has already shown the potential benefits of this approach.[162,163,164] Future research will clearly need to evaluate the toxicology of treated wastewater using standard bioassays and mutagenicity tests, but should also include novel toxicological techniques (e.g., sensors, bioassays) to more effectively analyze complex matrices such as produced water and develop in silico modeling that can effectively predict detrimental synergistic effects and long-term toxicity from chronic exposure.

3.9. Climate Change and Water Stresses

Climate change could adversely impact agricultural productivity through changes in rainfall patterns, more frequent occurrences of climate extremes (including high temperatures or drought), insect populations, and pest issues. The rate and severity of the change and the ability of producers to adapt to changes will impact what is produced.[165] At the other extreme, a changing climate is expected to increase the frequency of extreme precipitation events exacerbating water runoff, soil erosion, and the loss of soil carbon. Elevated temperatures also play a critical role in increasing the rate of drought onset, overall drought intensity and impact through altered water availability and demand leading to the depletion of surface and groundwater resources.[166] Figure 12 reveals the regions of the United States that are heavily irrigated and are under varying degrees of water stress. These areas could benefit from the development and use of nontraditional water sources to supplement existing sources or replace them altogether.

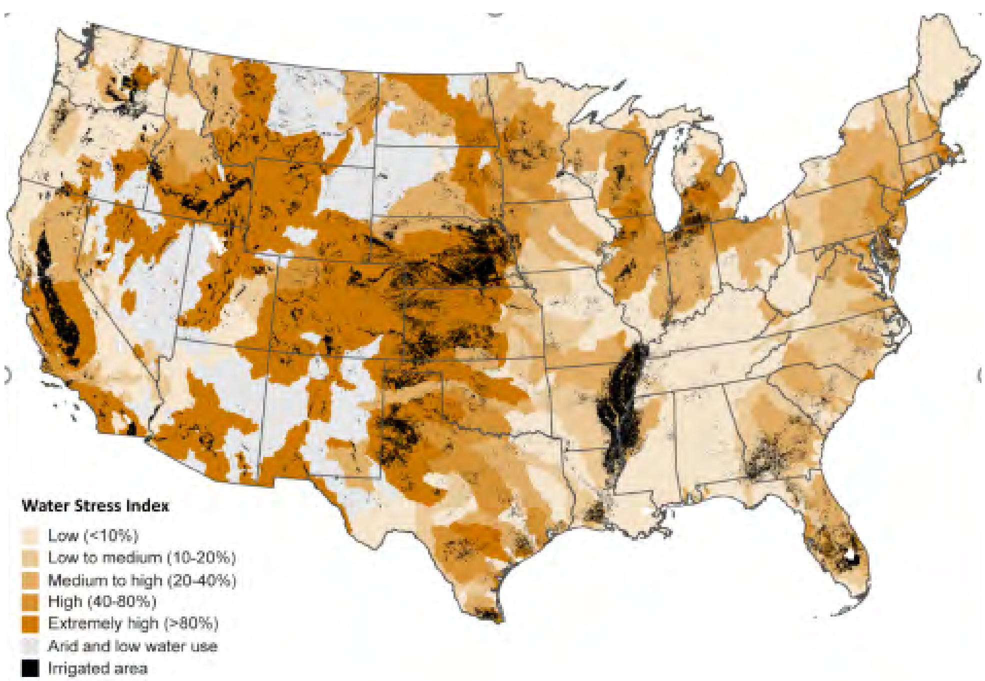
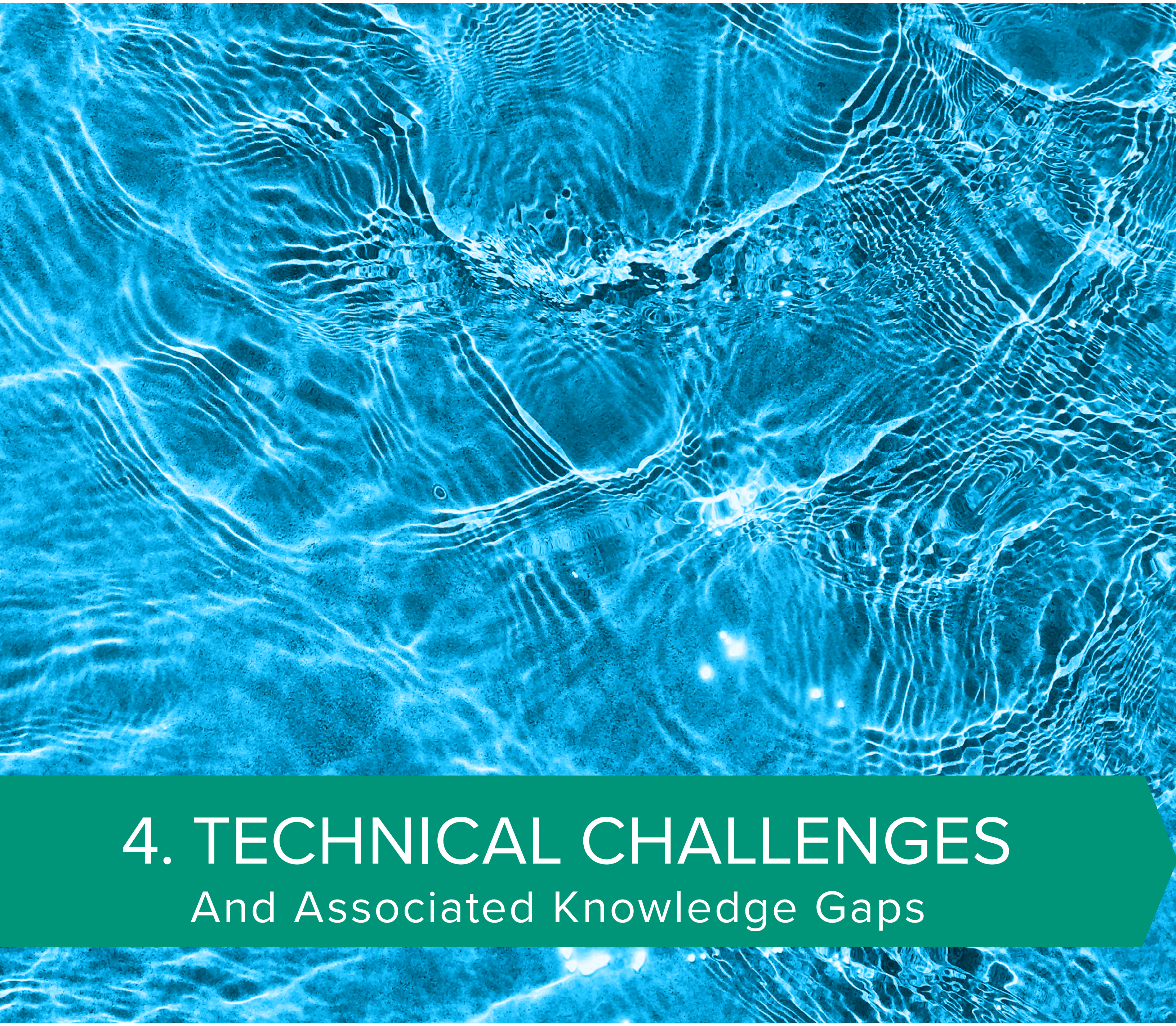


Figure 12. Irrigated areas (2012) and water-stressed areas (2015) across the contiguous United States

Source: GAO

3.10. Societal Barriers

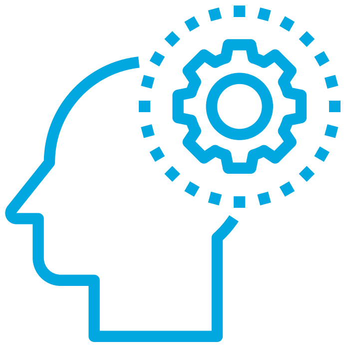
The success of using nontraditional water sources in the Agriculture Sector is shaped by technological, economic, and societal factors. There are numerous societal concerns towards the usage of recycled water in the Agriculture Sector. These include farmers' predisposition to, and the public's perception of, using recycled wastewater to produce food. A recent survey showed that even though farmers are concerned about water availability, only a small fraction of the respondents identified using a nontraditional water source in agriculture as 'very important.'[167] The ranking of the importance of using nontraditional water sources in agriculture was influenced mostly by farm size and primary water source. Furthermore, several studies have found that the public is reluctant to using reclaimed water for drinking purposes and other "high personal contact" uses.[168]



4. TECHNICAL CHALLENGES
And Associated Knowledge Gaps

Expanding the availability and reliability of using nontraditional source waters for the Agriculture Sector requires several challenges and knowledge gaps to be addressed.

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



These barriers have been identified through workshops and discussions with subject matter experts, as part of a structured roadmapping process. They are too large and far-reaching for any one organization to devote all the resources needed to develop suitable solutions.

NAWI intends to invest in promising technologies that are crosscutting across the PRIMA areas and that address some technical limitations discussed below.

4.1. Technical Challenges

4.1.1. Water Supply and Quality

Presence of chemical and microbial contaminants in nontraditional water sources. The composition of nontraditional water sources is often radically different from typical freshwater sources. The sustainable use of these sources requires removal of impurities that affect crop production, dairy, and meat processing industries. For instance, B in produced water, As in brackish water, Se in tile drainage, salts in meat processing wastewater, and persistent organic pollutants in municipal wastewater may require removal prior to agricultural uses. Thus, it is important that we fully understand the level to which we need to treat the water and the toxicity of this treated water to allow for sustainable reuse for agricultural purposes to prevent adverse impacts on crop, soil, and human health.

Proximity and accessibility to nontraditional water sources. A significant challenge with using alternative water sources for agriculture are the costs associated with their transport to the specific agricultural end user, and the costs associated with their storage. Some alternative water sources might be discharged into nearby traditional surface water supplies, but others might still require transport over large distances.

Regional and seasonal variability in agricultural water demand. Site and seasonal variability affect agricultural water demand. In addition, the demand for agricultural water varies with climate, weather, growing season, and crop requirements, meaning that nontraditional waters may require storage for use during periods of high demand. Surface storage is not only expensive to construct, but also decreases the land surface area available for profit-making agricultural activities when constructed on crop or pasture lands. However, without storage, the variable demand for agricultural water and the potentially variable alternative water supplies might be poorly matched at crucial times, such as the growing season for harvested crops. In addition, the competition for these water sources among different sectors (e.g., industrial, community) could constrain the continuous supply to agriculture.

Low cost of water from traditional sources in many locations. The treatment of nontraditional water for farming, dairy, and meat production will require sizable investments to fully develop technologies as well as manage the additional residuals and concentrates. Implementing new technologies will come with significant adoption costs. With traditional businesses, these can often be passed on to customers. However, this will not be viable with agricultural water users in many locations because fit-for-purpose water is already available at low or even no cost (e.g., precipitation).

4.1.2. Source Water Treatment Limits

Inefficient removal of agricultural-relevant contaminants found in nontraditional water sources. Bulk separation processes are an industry standard leading to waste materials that are non-homogeneous and of low value. Current bulk water treatment processes are limited in selectively removing constituents (e.g., Na^+, Cl^-, B, metals, and NORM) that can negatively impact crop growth while retaining beneficial ions (e.g., K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, NO^{3-}, and PO_4^{3-}) in the treated water. Depending on the nontraditional source water, reclaimed materials are collected in insufficient volumes (or, in some cases, huge volumes, as with salts in PW or brackish water) and have low market value; for this reason, the use of advanced technologies for selective separation and recovery of these constituents is rarely justified.

Limited options for treating brines produced in meat and dairy processing operations. Meat and dairy processing include isolated processes that produce high-concentration brines that require energy-intensive and costly treatments, inhibiting wastewater reuse in the industry and in irrigation, where high sodium and salinity levels can have negative effects on soil properties and crop health.

4.1.3. Resource Recovery and Waste Management

High costs and limited options for disposal of concentrated waste streams. Disposing of unwanted constituents and brines can be difficult and costly, and the hazard levels might be heightened with the use of nontraditional waters. The U.S. Environmental Protection Agency (EPA) has established a comprehensive regulatory program ensuring that hazardous waste is managed safely during its creation, transportation, treatment, storage, and disposal. The use of nontraditional waters will require expanded hazardous waste permits, possibly at considerable expense. In addition, the generation and disposal of concentrated waste streams containing hazardous wastes can create concerns over future liability.

High costs and limited options for management of brines and residuals produced by desalination processes. Current desalination processes cannot achieve high water recovery and pose significant challenges for the disposal of concentrate and residual waste. High-recovery desalination processes are needed to enhance water recovery (e.g., >98 percent) and minimize the residual volume for disposal.

4.1.4. Materials Capability and Durability

Fouling and scaling of treatment devices, piping, and irrigation systems. The stability, lifetime, and durability of process units used for water and wastewater treatment (e.g., meat and dairy processing wastewater) may be constrained by fouling and scaling. For example, current meat processing wastewater treatment systems need daily simple cleanings and more intense periodical cleanings to mitigate fouling and sludge buildup. Anti-fouling membranes and surfaces have been widely investigated, but these materials have only been tested in short-term experiments, and their effectiveness in long-term performance tests is still unknown. The use of nontraditional waters in the Agriculture Sector would likely add to the complexities in addressing scaling and fouling issues.

4.1.5. Toxicity

Toxicological assessment of newly identified nontraditional water sources for the Agriculture Sector. To date, insufficient data and research are available to fully capture the toxicity of nontraditional waters for agricultural operations, or the potential for synergistic effects among their components and component metabolites. Current toxicity assays are often not compatible with these nontraditional water sources due to matrix effects (e.g., high salt concentration). There is a need to understand the impact of treated nontraditional water sources on soil quality (chemistry and microbiome), crop health, and, ultimately, human health. The inability to evaluate the risks and impacts associated with the reuse of alternative water sources hampers the industry's investment in any alternative.

4.1.6. Land Availability

Limited land availability for certain types of natural treatment systems. Natural treatment systems typically require fewer operational personnel, consume less energy, and create significantly fewer waste materials. However, large areas are needed to ensure effective treatment without overloading the land. Dedicating agricultural land for natural treatment using wetlands comes at the expense of reducing growing areas. In addition, the complex composition of nontraditional waters would require a combination of varying plant types and novel sorbents for optimized treatment in engineered wetlands. Although natural treatment systems show promising removals of toxic constituents, such systems have not been widely adopted for agriculture due to their unstable performance when challenged with influent waters of varying quality and quantity.

4.2. Non-Technical Challenges

The list below identifies the non-technical challenges associated with using nontraditional water sources in the Agriculture Sector. The topics below are additional gaps that could limit the use of nontraditional waters. This list is not meant to be exhaustive, but rather a high-level report of the main ideas identified during the data collection phase.

4.2.1. Cultural and Societal

Cultural and societal barriers associated with the use of nontraditional source waters. There are numerous potential societal barriers to the use of recycled water for agricultural irrigation. First, farmers are concerned about water quality, food safety, and public health risks when nontraditional water sources are used. Moreover, consumer perception about the safety of recycled wastewater use during food production could affect the marketability of agricultural products and discourage farmers from using alternative water sources. Finally, farmers are often unlikely to adopt new technologies and management practices unless they are mandated and without considerable outreach and evidence of economic benefit. If the Agriculture Sector desires to utilize nontraditional water sources in their supply mix, strategies for gaining the consumers' and public's trust in using these different water sources also need to be developed.

4.2.2. Institutional

Institutional barriers for using nontraditional water sources in the Agriculture Sector. Rules, regulations, and laws stemming from various jurisdictions create challenges to using nontraditional water sources for agricultural, dairy, and livestock businesses. Water laws, and particularly water laws in Western States based on the doctrine of prior appropriation, may restrict or prohibit the reuse of applied irrigation water because return flows are often reserved for use by junior water rights holders. Moreover, food safety rules restrict the reuse of wastewater for meat processing.

4.2.3. Environmental

Environmental factors limiting access to nontraditional water sources. Climate change, varying weather patterns, drought, and drought cycles impact access to all kinds of waters. Controlling the carbon footprint when treating nontraditional source waters with high salinity values, pollution, and/or excessive nutrients will also be challenging. Crop sensitivities and residuals in the soil will determine the kinds of nontraditional waters that can be used, and the types of treatment steps needed to get them to the usable quality.

5. RESEARCH PRIORITIES

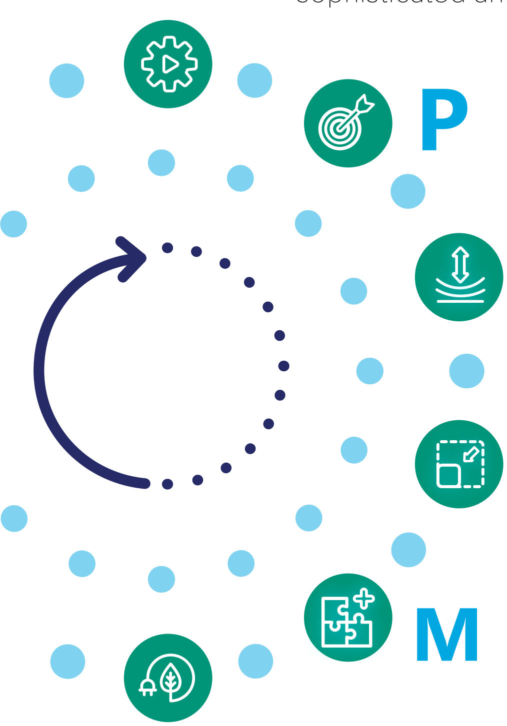
Areas of Interest for Agriculture End-Use Roadmap

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

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

Each identified AOI is followed by a short discussion on the current research challenges (a technology or problem that has not been adequately addressed by existing studies) and continues with specific TRL 2–4 research needs. Advances in these technologies and capabilities aim to reduce the cost of treating nontraditional source waters to the same range as marginal water sources, thereby achieving pipe parity.

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



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

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

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

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

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

5.1 Autonomous

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

A1. **Develop and use rapid, real-time, low-cost sensor groups and associated monitoring and control systems to detect target pollutants/constituents (e.g., pathogens, Se, B, As, P, and N), with focus on elements with fluctuating and wide ranges of concentrations.**

Challenges

Treatment and reuse of agricultural water with high temporal change in water quality requires the development of sensors that can provide real-time feedback for optimization of treatment and precise irrigation and can help accurately blend the treated water with other water sources. Sensors are currently used in agriculture and wastewater (for instance, in meat processing) treatment for a variety of purposes, including to measure soil moisture, conductivity, salinity, pH and temperature.[169] Current sensors often lack sufficient resilience and stability. Thus, sensor materials must be developed to resist fouling by salt, sediment, natural organic matter (NOM), or algae and be resilient to both wet and dry, as well as hot and cold, conditions. Integrated continuous monitoring is required in order to allow for optimized autonomous feedback systems and will require, in part, the ability of remote sensor systems to connect networks via WiFi, 5G, or satellite- or microwave-based connectivity. To help meet current and future agricultural water demands and wastewater effluent regulations, sensor technology for key agricultural constituents such as As, Se, B, pathogens, nutrients, pesticides, antimicrobials, organic matter, and algae should be the primary focus.[170,171,172,173,174,175,176,177,178,179]

Impacts

Rapid, low-cost sensors to detect target pollutants can improve performance throughout the Agriculture Sector (e.g., tile drainage systems and meat processing facilities). Other sectors will also benefit, especially in situations where the source water quality is variable and with stringent end-use quality targets. Real-time feedback for optimization of treatment, precision irrigation, or adjusting blending rates can reduce operation and maintenance costs and more consistently meet current and future regulatory targets (e.g., discharge limits for treated meat processing wastewater). The success of this AOI is enhanced if conducted in parallel with research on AOIs A2 and A3.

A1.

RESEARCH NEEDS:

- **Develop** sensors that are robust and work in harsh environments (e.g., freeze/thaw, high salinity, and high fouling) (TRL 1–3, 2–3 years).
- **Develop** sensors that are adaptable to a broad range of conditions (e.g., high salinity up to 50,000 mg/L) (TRL 3–4, 2–3 years).
- **Develop** sensor materials that are resistant to scaling, fouling, and corrosion (TRL 2–3, 3–4 years).
- **Develop** real-time (bio)sensors that can analyze multiple agriculturally relevant constituents (N, P, Se, As, B, TDS, PFAS, pathogens) simultaneously (TRL 2–3, 3–5 years).
- **Develop** sensors that can aid in autonomous water treatment and blending by incorporation of machine learning models and other AI systems (TRL 3–4 equivalent, 2–3 years).
- **Develop** sensors that can measure nutrient levels, algae growth, pathogens, pesticides, and other constituents related to the quality and delivery of stored agricultural water (e.g., ponds, aquifers) (TRL 2–3 equivalent, 3–4 years).
- **Develop** soil moisture sensors coupled with advanced weather forecasting that are connected to water storage ponds in order to help manage when and how much water is needed for precision irrigation (TRL 2–3, 2–5 years).

A2. Apply machine learning models and algorithms to data from sensors and other sources to develop specific agricultural water quality standards for process waters and source waters and to minimize the costs of alternative source water treatment, storage, and delivery.

Challenges

Machine learning is already used in agriculture for many purposes, including soil mapping, water management, crop yield prediction, carcass weight prediction, and image processing to detect water stress, pests, and disease.[180,181,182,183,184,185] However, the widespread adoption of "precision agriculture" and "smart farm technologies" has varied with technology and other factors.[186,187] Similarly, machine learning is already used in wastewater treatment to monitor influent conditions, optimize maintenance and treatment parameters, and predict effluent concentrations.[188,189,190,191,192,193,194] Alternative source waters must meet agricultural water quality requirements at costs that are competitive with traditionally used ground and surface water sources and that are consistent with the market values of irrigated crops, meats, and other agricultural products. In addition, waters discharged from agricultural operations, including meat processing plants, must meet reuse and other regulatory requirements as efficiently and economically as possible. Furthermore, treatment and reuse must account for source water qualities and agricultural water demands which may be highly variable based on time, location, prior use, and specific agricultural need. When applied to real-time sensor and other data from public sources (e.g., remote sensing), unit processes or treatment trains, and individual locations or wider geographical areas, machine learning models and algorithms have the potential to provide more specific source water treatment criteria, and to make the use of alternative source waters in agriculture more cost-effective.

Impacts

Using accurate machine learning models, the meat and dairy processing industry can treat water in real time for specific end-use quality targets (e.g., cleaning water, potable water, irrigation water), lowering treatment and waste disposal costs by avoiding excessive treatment of all wastewater streams. Cost reductions and performance improvements can extend to treatment applications in other sectors as well.

A2.

RESEARCH NEEDS:

- **Develop** machine learning models that can classify source waters for different treatment levels, including different fresh water blending rates (TRL 2–3, 3–5 years).
- **Develop** machine learning models that predict effluent parameters under different operating conditions, process parameters, and treatment train configurations (TRL 2–3, 3–5 years).
- **Develop** machine learning models that identify anomalies and the need for remedial action or that schedule preventative actions for improved process reliability (e.g., backwashing procedures for ultrafiltration membranes) (TRL 2–3, 3–5 years).
- **Develop** machine learning models that fine-tune agricultural water quality criteria for different alternative source waters, crops, soils, processes, and temporal water demands (TRL 2–3, 3–5 years).

A3. Develop automated digital network (e.g., IoT, SCADA, digital twins, AI) systems for integrated water quality data analysis, data-driven decision making, process monitoring and control for optimized water and wastewater treatment.

Challenges

Agriculture has significant large-scale regional and even site-to-site variability along with geographically distant features managed by generally decentralized, independent groups of growers, ranchers, producers, and processors. Advanced sensors, AI algorithms, autonomous systems, and other technological solutions require suitable means of support for their development and continued operation. Without effective automated digital networks, agriculture will continue to adopt costly manual interventions, due to the lack of reliable and secure data streams for analysis and control of water treatment systems, the inability to verify/enforce regulations, and economically infeasible advanced technology solutions.[195] NAWI's Water-TAP^3 Water TAP^3 (Water Technoeconomic Assessment Pipe-Parity Platform) analysis of the San Luis Demonstration Treatment Plant, a facility that treated saline tile drainage in California, showed that ultrafiltration (UF) and RO treatment processes account for a significant portion (approximately 70 percent) of the levelized cost of water. Advances in automated digital networks could optimize this treatment and other process steps further.

Impacts

Without effective automated digital networks, there will be continued costly onsite and manual interventions, a lack of reliable and secure data streams for analysis and control of water treatment systems, an inability to verify or enforce regulations, and economically infeasible technology solutions. These will provide the foundation for other AOI advancement but, in contrast to other sectors, are not yet widely available in the Agriculture Sector.

A3.

RESEARCH NEEDS:

- **Advance** the digital information-exchange infrastructure necessary using connected sensors, software, and other technological solutions (TRL 3–4, 2–3 years).
- **Integrate** the automated digital network with existing agricultural operations and permit easy adoption and continued use by the system users (TRL 3–4, 1–3 years).
- **Optimize** the automated digital network to consider the issues of interoperability, modularity, adaptability, and usability with respect to existing digital networks and human operators (TRL 3–4, 2–4 years).
- **Develop** a scalable, secure, and resilient automated digital network to address the implementation challenges of modern cyber-physical systems (TRL 3–4, 3–4 years).
- **Develop** watershed-scale predictive digital tools focused on optimizing energy and salinity management costs while achieving salinity related water quality goals throughout the water basin (TRL 3–4, 2–4 years).

A4. Develop an autonomous system that automates and optimizes the procedure of membrane cleaning and membrane replacement during desalination of wastewater.

Challenges

In meat and dairy processing, wastewater must be desalinated for both reuse and discharge. Wastewater desalination technologies are challenged with the need for daily, and more intense periodical cleanings due to the presence of proteins. The technologies implemented require flushing and cleaning processes to mitigate fouling and sludge build-up in the systems. Desalination of other source waters, such as tile drainage and PW also requires cleaning and flushing. Stopping wastewater treatment during cleaning processes is a hindrance to the efficiency of the treatment facility. Therefore, affordable pre-treatment and autonomous cleaning technologies that relieve the need for frequent maintenance are required to advance desalination processes (e.g., by pre-emptively removing oxyanions, emulsified oils, and other constituents that increase the need for cleaning).

Impacts

In the United States, 24 percent of all food industry water is used for meat processing and 12 percent for dairy and cheese production.[196] For the former industry, adopting desalination for hide brining wastewater could recover more than 60 percent of the salts for reuse (See Section 3.3.2, Table 1). The dairy and cheese industry, which produces six times more wastewater by volume than is consumed, may have similar opportunities for salt recovery (See Section 3.1, Figure 6).[197] In both industries, improving the salt and protein separation processes could increase salt reuse at a lower cost due to fouling and scaling mitigation.

A4. RESEARCH NEEDS:

- **Develop** a desalination technology that automatically mitigates fouling and sludge build-up through means of pre-emptive measures or automatic cleaning that do not require shutdown of treatment systems and other relying technologies (TRL 2–3, 2–4 years).
- **Improve** the cost-efficiency and performance of desalination technologies by providing automated pre-treatments to reduce fouling and required membrane cleaning processes (See A2, Research Need 3) (TRL 3–4, 2–4 years).

5.2. Precise

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

P1. **Develop a low-cost, selective method to separate contaminants that may adversely affect agricultural production or meat and dairy processing, or negatively impact public health and/or agro-ecosystems.**

While there is a plethora of contaminants of potential concern with respect to the PRIMA alternative water sources (e.g., B, Se and other oxyanions, emulsified oil, NORM species like radium, biocides, surfactants, halogenated components, disinfection by-products, microbially resistant genes, and contaminants of emerging concern such as pharmaceuticals, personal care products, endocrine disrupting chemicals, and fluorinated organics), this research objective targets and selects a few of these contaminants (e.g., B, Se, and oil and grease) due to their unique importance within agriculture or meat processing. Selective separation of contaminants will mitigate the negative environmental and public health impacts of utilizing improperly treated water, and present an opportunity for valuable resource recovery including water and essential nutrients (e.g., Se).

Challenges

Agriculture is a major user of groundwater and surface water, accounting for 80 percent of the nation's consumptive water use and over 90 percent in many Western states.[198] The increase in competition for water supplies among agriculture, industry, and the community sectors has driven the Agriculture Sector to tap into nontraditional water sources such as storm water, brackish aquifer water, municipal wastewater, and industrial wastewater. Sustainable use of these sources requires removal of impurities that affect agricultural and dairy and meat processing industries. Moreover, agricultural wastewaters must meet standards for discharge and/or reuse within agriculture or other sectors, and valuable constituents should be separated, concentrated, and marketed. The main challenges with treating non-conventional sources for application in agriculture are the high TDS or salinity concentrations, high organic content, and poor removal of constituents in processes targeting bulk water treatment. These substances must be addressed through precision separation. For example, heavy metals (e.g., in municipal wastewater), oil and grease (e.g., in meat processing), and specific ions such as B (e.g., in produced water) and

Challenges, cont.

Se (e.g., in tile drainage) are representative of the types of contaminants requiring precision separation. If not properly treated, these nontraditional water sources can impact public health, crop growth and aesthetic quality, and the soil's physicochemical and biological properties of the agro-ecosystem and neighboring areas.[199]

- **Boron (B) removal**: B is an essential micronutrient for many plants,[200] but high concentrations (e.g., > 0.5-1 mg/L) of B in irrigation water can significantly reduce crop yields.[201] Current strategies to selectively remove B from water include ion exchange and membrane separation.[202] Successful ion exchange can be accomplished using B selective chelating resins (e.g., N-methyl-D-glucamine (1-amino-1-deoxy-D-glucitol), [NMDG]), but limitations include the cost of regeneration and resin replacement. Reverse osmosis has been applied to agricultural waters for a range of other contaminants.[203] At neutral pH, the dominant B species in water is the small, neutral boric acid, which is not effectively rejected by conventional RO membranes due to limited size exclusion and charge repulsion.[204] Thus, the rejection rate of B by conventional RO membranes is highly dependent on the pH of the feed and on membrane properties, and rarely exceeds 65 percent for brackish water reverse osmosis (BWRO) and 95 percent for seawater reverse osmosis (SWRO) at neutral pH (6-8).[205] Treatment trains often employing multi-stage membrane or hybrid processes have potential for achieving adequate B removal for reuse applications; however, these additional steps can drastically increase costs, and pH adjustments may lead to membrane scaling.[206] These challenges limit the feasibility of RO for desalinating nontraditional water sources with high concentrations of inorganic species (e.g., Ca^{2+}, CO_3^{2-}, SO_4^{2-}).[207]

- **Oil and grease removal**: Dissolved and dispersed oil, grease, and other organics represent major components of industrial wastewater (e.g., meat processing and produced water). Conventional treatment technologies that are density-based (e.g., flotation aided by air bubbles, hydrocyclonic separation, centrifugation, settling) require a prolonged retention time. On the other hand, chemical treatment (e.g., coagulation, flocculation) is inefficient in removing finely dispersed oil.[208] Membrane technology can complement rather than replace conventional methods to achieve a high-quality permeate.[209]

Challenges, cont.

Selenium (Se) removal: Se is both an essential nutrient and a contaminant of concern for human and ecosystem health. With respect to agriculture, low Se soil levels (< 1 mg/kg) are beneficial for plants, but higher levels can cause toxicity for crops.[210,211] Se is also a concern in agricultural drainage water, particularly in the Western United States. It is often present in water as an oxyanion of either Se (IV) or Se (VI). Treatment is required for water with high concentrations of Se due to its extreme toxicity and potential food chain biomagnification.[212] Recovered Se can be used in several fields including technology, medicine, and manufacturing (e.g., solar cells, photocopiers).[213] There are several technologies that have been studied for Se removal from water including biodegradation, sorption, membrane separation, phytoremediation coagulation, ion exchange, and catalytic reduction. However, there are several challenges with either the reduction process or Se recovery, especially in complex waters. For example, the presence of other oxyanions, particularly sulfate may inhibit the biological reduction of selenate and lead to the precipitation of selenium sulfide. Separation of biologically produced Se nanoparticles can be energy intensive. There is a clear and present need to develop a sound mechanistic understanding of the microbiological, physical, and electrochemical processes that are associated with Se-laden wastewater treatment, and innovative cost-effective technologies for the treatment and recovery of Se as a valuable resource.

Impacts

Due to sedimentary deposits, climate, agricultural activities, and lakes and ponds with no outlets to flush accumulating salts, nine Western states have areas that have existing Se problems or have the potential to develop Se problems that could be addressed if a cost-effective separation process could be developed.[214] Se removal could also benefit the electric power (e.g., coal mining wastewater) industry. B is typically removed with a double-pass RO system for reuse applications. Developing a B removal process that obviates the need for a second pass of RO could potentially reduce the levelized cost of water by 10–20 percent.[215,216] B removal might improve the quality of tile drainage water as well as treat other nontraditional source waters (e.g., seawater, brackish water, produced water) for reuse to irrigate crops if costs are affordable enough for the Agriculture Sector. Removing proteins from meat and dairy processing wastewaters before desalination will decrease the need for membrane cleaning and maintenance, which represent a significant portion of the total operational and maintenance expenses. In one analysis of a meat processing treatment train by NAWI, the operation costs for these processes were twice the cost of all other treatment processes.

P1.

RESEARCH NEEDS:

Boron

- **Conduct** an updated[217] TEA of non-chemically intensive RO pre-treatment processes (e.g., electrodialysis, loose nanofiltration) to remove potential ionic foulants/scalants from potential agricultural source waters (TRL 2–3, 1–3 years).
- **Develop** a single-stage B removal process that obviates the need for multi-stage membrane or post-treatment ion exchange (e.g., ligand-functionalized membranes, electrically conducting membranes, defect-free membranes, electrocoagulation) (TRL 2–3, 1–3 years).

Oil and Greases

- **Integrate** membrane-based and other conventional methods to treat oily wastewater to harness the advantages and circumvent the shortcomings of each (e.g., hybridizing adsorption with membrane filtration where the membrane rejects the adsorbent) (TRL 2–3, 1–3 years).
- **Develop** membrane systems that can leverage the inherent properties of the foulant (e.g., systems with rotating flows that rely on the buoyancy of the foulant [i.e., oil droplet] to be diverged from the membrane surface limiting fouling) (TRL 2–3, 2–4 years).
- **Develop** oil/water treatment systems with dual roles of separating oil and water and creating high-quality oil and water streams (e.g., hydrophobic membranes) (TRL 3–4, 2–3 years).

Selenium (Se):

- **Develop** novel treatment processes for reduction and energy-efficient recovery of Se and elucidate the biological and physiochemical mechanisms responsible for treatment. Research should determine kinetics, identify relevant bacterial populations (if employed), and include an assessment of reactor design and materials. In addition, effective system-control technologies should be assessed (TRL 3–4, 2–4 years).
- **Develop** mechanistically based mathematical models to support process design, economic analyses, and future research and development. The mathematical models should be capable of supporting control technologies (TRL 3–4, 2–3 years).
- **Advance** the performance of physical or chemical technologies (e.g., electrocoagulation) for removal of Se prior to desalination (if the water source is saline) and couple these processes with Se recovery processes (TRL 2–3, 1–3 years).

Other contaminants

- **Develop** relatively low-cost and energy-efficient destructive technologies (e.g., electrocoagulation) for treatment and recovery of agriculturally relevant low-concentration organic contaminants without the generation of hazardous waste streams (See E1, Research Need 1) (TRL 2–3, 1–3 years).

P2. Develop low-cost, selective separation for valorization of wastewater (e.g., meat processing water, tile drainage) by, for instance, extracting nutrients such as N, P, K, and protein.

Challenges

Agricultural source wastewaters have unique compositions and challenges in the selective removal of constituents. Wastewater from meat processing has high concentrations of N, P, organics, and solids. Current treatment technologies for these wastewaters are typically unsuccessful in the recovery of constituents necessary for waste-stream valorization. The main objectives of the meat processing industry are to develop technologies that will remove proteins and organics in pre-treatment, technologies to improve the concentration of solids in effluents after desalination, and technologies to remove higher amounts of N.[218,219] Furthermore, the selective removal of N and P could result in beneficial reuse in agriculture through the production of fertilizer. For tile drainage reuse, the challenge of valorization is removing from water everything toxic to plants and soil (salts, microbes, heavy metals, or CECs) while leaving other valuable nutrient products in the water, since this water could be reused on-site for fertigation of crops.[220,221,222,223] Produced water from resource extraction proves invaluable unless B can be removed while lowering TDS levels.

Impacts

In the Midwestern and Eastern United States, tile drainage contributes large quantities of nutrients to surface waters, up to 10 kg of N per hectare per year (4.05 kg of N per acre per year) in the most polluted areas, according to the 2012 USGS SPARROW (SPAtially Referenced Regression on Watershed attributes) model.[224] Selective separation of nutrients from drainage water could dramatically improve water quality and reduce eutrophication in lakes, streams, and rivers, if costs could be managed. The P and/or N removed from these waters, as well as meat and dairy processing wastewater, could potentially be recycled to provide fertilizers for crops. Alternately, if salts that are toxic to crops could be selectively removed, the remaining nutrient-laden water could be reused as a form of fertigation.

P2.

RESEARCH NEEDS:

- **Develop** highly selective membranes or treatment systems capable of differentiating between closely related ions (i.e., similar charge and structure). One example is the removal of toxic ions (e.g., B, Na^+, Cl^-) while retaining beneficial ions (e.g., NO_3^-, PO_4^{3-}, K^+, Ca^{2+}, Mg^{2+}) that can serve as nutrients, (TRL 2–3, 2–4 years).
- **Create** cost-effective systems that are successful in recovering N and P from meat processing wastewaters for use in the production of fertilizers (TRL 2–3, 2–4 years).
- **Develop** technologies that recover proteins and other valuable organics in meat and dairy processing wastewater (TRL 2–3, 1–3 years).

P3. Develop high-performance and cost-efficient materials for precision separation and easy in situ regeneration, such as adsorbents (e.g., modified zeolite, metal organic framework materials), ion exchange resins, and membranes.

Challenges

While conventional RO membranes perform salt/water separations well, the rejection of certain contaminants (e.g., small, neutral solutes) limits the reuse potential of highly contaminated, nontraditional waters. Membrane research has often focused on achieving higher water permeabilities, leading to increased volume throughput, yet solute-selective separations still present immense challenges for water reuse.[225] Thus, the development of novel water treatment processes utilizing advanced materials to selectively remove target contaminants in an energy efficient manner is essential. Membranes that achieve separations based on mechanisms beyond size exclusion and charge repulsion, such as those functionalized with chelating groups to act as hybrid membrane sorbents, have been suggested for several solutes including heavy metals.[226] Yet more work is needed in this space to fully realize the potential of these materials in real-world systems. In particular, research should focus on relating material properties (e.g., solute/ligand binding constants, uptake capacities) to overall performance (e.g., recovery, rejection, regeneration potential and frequency). Multifunctional materials can also be leveraged to achieve solute-specific separations through several mechanisms, including adsorption, catalytic degradation, and disinfection,[227] and the incorporation of these advanced materials into novel treatment trains will enable precise tuning of size, morphology, and chemical structure of treatment materials to simultaneously achieve several treatment goals (e.g., fit-for-purpose water generation, resource recovery).

Impacts

Incorporation of multifunctional materials into treatment trains (e.g., advanced membrane materials for selective removal or recovery of nutrients; cost-effective adsorbents that serve a dual function as adsorbent and catalyst for the removal of inorganic constituents; or selective separation and destruction of recalcitrant organic pollutants) can reduce the overall levelized cost and reduce the footprint of treatment trains.

P3.

RESEARCH NEEDS:

- **Design** cost-effective materials that modify the affinity and pore space geometry of membranes to prevent irreversible fouling and aid in membrane cleaning (TRL 2–3, 1–3 years).
- **Advance** membrane materials for the selective removal or recovery of constituents (e.g., highly crosslinked defect-free membranes or functionalized membranes to capture solutes during permeation) (TRL 2–3,1–3 years).
- **Evaluate** the practical applicability and functionalization of adsorbents (e.g., metal organic framework, modified zeolite) in terms of cost, stability, and recyclability (TRL 3–4, 2–4 years).
- **Develop** novel cost-effective adsorbents that serve a dual function as adsorbent and catalyst (e.g., engineered clays) for the removal of inorganic constituents (TRL 2–4, 2–4 years).
- **Develop** novel support materials for fixed-film biological systems that facilitate metal ion reduction and recovery (TRL 2–4, 2–4 years).

P4. Explore selective removal of Na^+ (and Cl^-) using electrochemical/ electro-membrane processes to reduce the SAR for irrigation or recover salt and add back to brining during meat processing.

Challenges

High amounts of sodium and chloride in nontraditional water can cause salt accumulation in soil and damage to plants during irrigation.[228,229,230] Selective separation of Na^+ and Cl^- from other ions, such as Ca^{2+}, Mg^{2+}, K^+, NH_4^+, and NO_3^- is also important for closed-loop soilless or hydroponic systems, because those are nutrients for plants and should be retained in irrigation water. Besides, selective separation of NaCl also allows salt recovery in meat and dairy processing , such as adding salt back to brining during meat processing. Currently, there are a few meat processing companies that use energy-intensive thermal/mechanical evaporators to treat hide brine to meet chloride discharge standards. The solids could be potentially recovered for beneficial use.

There are limited technologies that can selectively separate Na^+ and Cl^- from other ions. For example, monovalent permselective ion exchange membranes are the state-of-the-art technologies for selective separation of monovalent ions from divalent and multivalent ions. However, selective membranes are very costly, and/or the selectivity is affected by the ionic strength of the water and decreases with increasing salinity in water.[231,232] Also, there are no commercial separation membranes available that can effectively separate the ion species that share similar physicochemical properties, such as Na^+ and K^+, the latter being a required nutrient for plant growth.[233]

Impacts

Low volume, high salinity flows can contribute to 64 percent of salts in beef processing wastewater flows (See Section 3.3.2, Table 1). Selective desalination can reduce the SAR so the water can be reused for irrigation and provide salts that can be reused in future brining. Purification of salts in saline tile drainage (e.g., sodium sulfate, sodium chloride, calcium sulfate) can offset the cost of treatment if the salts can be reused for food processing or sold to other industries. Treated tile drainage with lower SAR can be reused widely for irrigation. For example, the tile drainage reuse potential in California's San Joaquin Valley can be calculated based on estimates of irrigation volumes[234] and area of tile-drained farmland.[235] If 80 percent of irrigation volumes are consumptively used and half of the estimated available tile drainage is treated, 14 billion of liters per year (3.7 billions of gallons per year) of irrigation water could be potentially produced. This can provide irrigation water for a water-stressed area and, assuming a safe brine disposal or reuse opportunity is found, salts can be removed or recovered reducing its accumulation in soil and water resources.

P4.

RESEARCH NEEDS:

- **Develop** low-cost, highly selective resins, membranes, or electrodes for Na^+ and Cl^- ions from other monovalent and multivalent ions, such as polymeric, ceramic, or liquid supported membranes (TRL 3–4, 2–4 years).
- **Understand** the physical, electrochemical interactions of the membranes/materials with electrolytes (TRL 2–3, 2–3 years).
- **Develop** transport models to simulate and predict the permselectivity of the ions over a range of electrical potential, and varying water composition and operating conditions (TRL 3–4, 2–3 years).

5.3. Resilient

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

R1. **Develop technologies that do not use chemicals, that reduce chemical consumption, that are based on in situ generation of chemicals to minimize chemical transport, storage, and handling.**

Challenges

Treating nontraditional water sources (e.g., municipal wastewater, brackish water, meat processing, produced water from petroleum production) for irrigation purposes requires the addition of chemicals such as coagulation aids, corrosion scale inhibitors, disinfectants, and conditioners. The addition of chemicals can impact process units and equipment (i.e., corrosivity) and generate toxic secondary byproducts. For example, desalination of brackish water produces a high-quality permeate (e.g., low salinity); meanwhile, the desalinated water is corrosive due to its acidity and the lack of buffering capacity, which makes remineralization (e.g., adding calcium carbonate/calcite, magnesium sulfate) an important posttreatment prior to agricultural application. Other sources such as meat processing and municipal wastewater would require disinfection (e.g., Cl_2).[236,237] The main challenge with chemical additives is the cost of transportation; which was recently estimated as $2.53/ton-mile via railcar (the most efficient transportation method).[238] In analyzing the SVRP using the Water-TAP3 tool, the post-treatment chlorination step accounted for seven percent of the levelized cost of water and five percent of the electricity demand. As more advanced treatment technologies are developed and applied in the water industries, more types of chemicals (e.g., ozone, hydrogen peroxide) are used. These chemicals bring new challenges, including on-site storage of hazardous unstable chemicals (e.g., Cl2, hydrogen peroxide), transportation, and tail waste management.

Impacts

The cost of transporting, handling, and discharging chemicals may account for 5 to 20 percent of the total O&M expenses in RO plants. Improved chemical-free technologies that substantially reduce transportation and handling costs without offsetting those savings from higher energy consumption and maintenance expenses would benefit all the source waters used in agriculture (e.g., municipal wastewater, brackish water, and agricultural wastewater).

R1.

RESEARCH NEEDS:

- **Develop** low-cost, robust, and scalable technologies (e.g., electrocatalytic systems) that are based on in situ generation of chemicals to minimize the cost of chemical transport, storage, and handling (e.g., ozone, hydrogen peroxide, Cl) (TRL 3–4, 2–3 years)
- **Develop** novel, durable, resilient, stable, and scalable homogeneous or heterogenous advanced oxidation processes that can generate oxidants (e.g., hydrogen peroxide) in situ that are powered by electricity or renewable energy sources and whose function is controlled by autonomous feedback control systems for adjustable performance based on variations in source water quality (TRL 3–4, 4+ years).
- **Perform** long-term studies that evaluate system performance with real water matrices and of varying water quality to challenge system performance under extreme operating conditions. Evaluate methods of system regeneration without using chemicals such as electrically driven processes (e.g., electromagnetic fields, ultrasound) (TRL 3–4, 4+ years).

R2.

Develop dynamic biological treatment systems that are resilient to variations in water quality, temperature, and toxics. These systems should also be optimized for recovery or transformation of nutrients and removal of CECs.

Challenges

Conventional wastewater treatment plants based on activated sludge processes can effectively remove biodegradable organic matter and ammonia nitrogen and achieve some degree of disinfection; however, those plants have not been specifically designed 1) to remove toxic and/or refractory organic pollutants[239] and 2) to recover valuable nutrients.[240] For example, irrigation using reclaimed water can reduce freshwater demand, but it may also introduce toxic and/or refractory organic pollutants such as antibiotics, antifungals, PPCPs, EDCs, and PFAS into the soil and groundwater.[241,242,243,244,245,246,247,248,249] In particular, the extreme persistence of PFAS creates challenges for treatment technologies typically included in conventional wastewater treatment trains (about 17 percent removal).[250,251] The recent development in agro-based adsorbent materials (e.g., biochar) may provide such an opportunity to reduce the risk of toxic and/or refractory organic pollutants from reclaimed-water irrigation[252,253,254] and recover nutrients from wastewater for agriculture.[255] However, further investigations are still needed to 1) synthesize low-cost agro-based adsorbent materials for selective recovery of nutrients in combination with biological processes for agriculture and 2) test the effects of both nutrients and pollutant-laden adsorbent materials on the soil ecosystems and aquatic environments.

Aerobic biological treatment technologies, including activated sludge and biological membrane processes, are the most common wastewater treatment technologies[256] However, the efficient and stable operation of conventional wastewater treatment processes can easily be disturbed by water quality fluctuations environmental conditions, and the inclusion of toxic compounds in influents.[257] Membrane bioreactors (MBRs),, which combine activated sludge treatment and membrane separations, have been identified as an innovative technology for water reclamation because of their superior stability, lower space requirement, and excellent ability to remove various micropollutants.[258,259,260] Although aerobic/anaerobic MBR processes show promising removals of toxic and/or refractory organic pollutants and pathogens, MBRs have not been widely adopted for treating agricultural wastewaters because of unstable performance due to seasonal perturbations of agriculture water input conditions and high maintenance requirements (for example, severe membrane fouling). Therefore, there is an urgent need to 1) optimize MBRs for agro-industrial wastewater and agricultural tile drainage, and 2) develop hybridized-MBRs that incorporate other physicochemical/electrochemical methods to maintain high and stable performance despite sudden perturbations of the input conditions and operating conditions.

Impacts

Aerobic and anaerobic biological treatment systems have proven to be efficient in terms of energy consumption and chemical usage and are cost-effective at many municipal and agricultural WWTPs. However, many CECs and salts are not efficiently and reliably removed by conventional WWTPs. The development of hybrid biological treatment systems could benefit many centralized and decentralized WWTPs in both sectors.

R2.

RESEARCH NEEDS:

- **Develop** efficient and low-cost aerobic/anoxic/anaerobic biological treatment processes (including, but not limited to, advanced constructed wetlands, anaerobic digesters, aerobic and anaerobic MBRs) and advance the fundamental understanding of underlying mechanisms for the enhanced removal of toxic and/or refractory emerging organic pollutants (such as antibiotics, PFAS, and xenobiotics) from agro-industrial wastewater and agricultural tile drainage (TRL 3–4, 2–4 years).
- **Design** and manufacture sustainable agro-based adsorbent materials that 1) ensure closed and environmentally favorable recycling of valuable macro-nutrients (especially N, P, and K) and micro-nutrients (e.g., iron [Fe], Mn, and B) in combination with biological processes for agriculture and 2) avoid the discharge of those nutrients to water bodies (TRL 2–3, 1–2 years).
- **Develop** dynamic and resilient alternative hybrid physiochemical/electrochemical and biological processes to maintain high and stable performance despite sudden perturbations of the input conditions and operating conditions for the safe reuse of agro-industrial wastewater and tile drainage in agriculture (TRL 2–4, 4+ years).

R3. Develop technologies for effective water treatment and monitoring that will allow sustainable long-term storage of water in aquifers and ponds.

Challenges

Cost will always be a primary challenge for agriculture because farmers work with small economic margins, so any on-site monitoring and/or treatment system of irrigation water must be low-cost and energy efficient, but also highly effective at treating water destined for crop production. Long-term storage of water or monitoring via sensors will require technologies that are low-maintenance and resilient to forces of the natural environment. Any modular treatment systems need to account for a wide range of inorganic and organic constituents that have considerable temporal variation depending on both local climatology and management practices unique to each farm. Due to the highly variable characteristics of tile drainage, monitoring systems must be able to conduct remote, real-time analysis of stored water so farmers can track nutrient loads applied to fields, monitor salinity, and prevent cross-contamination of pesticides that have the potential to leach from fields during high-intensity weather events.[261] The state-of-the-art agricultural water storage and treatment systems are referred to as “tailwater recovery systems” or “drainage water recycling.” These systems store tile drainage in reservoirs or wetlands that can be pumped upstream to irrigation systems and reapplied to fields when natural precipitation is insufficient. These systems are only applicable when the drainage consists of non-toxic constituents, as is common in the Midwest and Eastern states.[262]Aside from natural degradation processes in the stored water (e.g., sedimentation or denitrification), there is no evidence of advanced treatment systems or water-quality sensors being used in agricultural settings before this water is reapplied as irrigation.

Impacts

Agricultural cropland across the country would benefit from improvements to long-term drainage storage combined with passive treatment that could supplement irrigation needs during dry periods in the growing season and minimize discharge of polluted water during large precipitation events by capturing non-point source pollutants in these passive treatment reservoirs.

R3.

RESEARCH NEEDS:

- **Develop** membranes for selective removal of toxic salts such as Na, Se, or B that treat stored water on-site before water is applied to crops as irrigation. Selective removal is vital because valuable fertilizer products such as nitrate, phosphate, or other micronutrients must remain in solution to improve pipe parity by lowering fertilizer costs for farmers through recycling of these nutrients (TRL 2–3, 2–4 years).

- **Evaluate** natural treatment options of stored tile drainage in order to minimize on-site treatment costs/ energy consumption since natural systems are generally less expensive than modular membrane systems. These treatments could include:

  algae mitigation through natural consumers such as fish or invertebrates,

  drainage systems that direct water through constructed wetlands prior to storage (potential value product if an economic crop such as alfalfa or Jose Tall Wheat Grass can be grown), or

  growth of biofuel producing algae in storage ponds (potential value product) to remove fertilizer nutrients (AOI R6 below) (TRL 2–3, 2–4 years).

R4.

Develop engineering and materials science approaches that address material/system stability, lifetime, and durability challenges based on mechanistic understanding of degradation/stability/durability. For example, in the case of thermal treatment of hypersaline brines, expensive materials (e.g., titanium) are often used to avoid corrosion, and low-cost material membrane solutions often foul when encountering highly saline brines.

Challenges

Wastewaters relevant to the Agriculture Sector typically possess complex compositions. For example, municipal wastewater, which contains abundant nutrients and is potentially used for agricultural irrigation, has high fouling potential due to the diverse organic and biological foulants present in the wastewater matrix. Similarly, wastewater generated from the meat and dairy processing industries often contains not only high salinity but also high protein content. Further, mineral scaling occurs and compromises the performance of water treatment when brackish water is treated for agricultural irrigation. As a result, the stability, lifetime, and durability of technologies used for water and wastewater treatment in the Agriculture Sector are constrained by a combination of fouling and scaling.

The topics of fouling and scaling have been investigated in literature, particularly in the field of membrane technology. Anti-fouling membranes and surfaces, including those with special wettability and grafted with biocidal materials, have been developed, with the underlying mechanisms of fouling resistance elucidated.[263,264,265,266] However, such materials are typically tested in short-term experiments, and their effectiveness in long-term performance tests is unknown. Compared to extensive studies on organic and biological fouling, similar knowledge on inorganic scaling and the corresponding scaling-resistant membranes has yet to be established.[267] Particularly, it is unknown whether membrane innovation or process innovation (e.g., pretreatment, the use of anti-scalants) is more feasible and economical for scaling mitigation. Further, the current knowledge has not been connected to the Agriculture Sector, with the fouling and scaling behaviors in the context of agricultural usage yet to be fully understood. The current progress on fouling- and scaling-resistant materials are not tailored to the Agriculture Sector. Developing novel materials that adapt to the characteristics of water and wastewater related to the Agriculture Sector, therefore, is essential to practical implementation of water and wastewater treatment to achieve pipe parity and improve water sustainability of agriculture.

Impacts

All treatment technologies are limited by stability, reliability, and durability of materials and systems. For example, tile drainage is prone to mineral scaling while meat and dairy processing are affected by fouling and, in highly saline solutions, scaling. If costs are not excessive, process and material improvements can lower system O&M costs.

R4.

RESEARCH NEEDS:

- **Identify** key characteristics or chemical species that adversely affect the performance of water and wastewater treatment for the Agriculture Sector (TRL 2, 1–2 years).
- **Design** and fabricate robust and resilient materials tailored to the characteristics or species identified above. The effectiveness of such materials needs to be demonstrated with a long-term performance test (TRL 2–3, 1–2 years).
- **Develop** techniques that monitor the alteration of key material properties (i.e., the properties that endow the materials with robustness and resiliency) during water and wastewater treatment (TRL 3–4, 1–3 years).
- **Design** a pre-treatment technology that, without increasing maintenance or cost, enables the implementation of low-cost membrane technologies, such as membrane distillation, for the resilient desalination of wastewater from meat and dairy processing industries. These technologies would have to remove constituents that cause fouling, cleaning, and replacement of parts in the membrane desalination technologies such as proteins, oils, and fats (TRL 2–3, 2–4 years).
- **Improve** upon the costs and reliability of high-performance desalination technologies, including the expensive material costs of mechanical vapor recompression (MVR) and the constituent-sensitivity of submerged combustion evaporation (TRL 3–4, 1–3 years)

R5.

Develop more reliable low-energy natural systems (e.g., resilient engineered wetlands) enabling effective response to varying water quality and quantity. These wetlands should be optimized for removal of nutrients, organic contaminants, and pathogens. Implement recovery of metals such as Se by hyper-accumulating plants or novel sorbents.

Challenges

The primary challenge of constructing these natural systems will be the availability of land because in an agricultural system, land not used for the growth of crops is money lost for the farmer. Agricultural wastewater contains a wide range of constituents, so these natural systems will need to have the versatility to remove the above-mentioned constituents through a combination of varying plant types, novel sorbents, and natural physical processes.[268,269,270] Temperature of the influent water can have a large effect on the removal efficiency and the plant species. There is a need for engineered wetlands that can operate under seasonal climate changes while maintaining consistent removals. These wetlands are used on a limited basis in agriculture, but primarily in a manner that improves the quality of the drainage water prior to environmental discharge and not for reuse within the agricultural system.[271,272] In addition to fertilizer and sedimentation removal, these systems have the potential to remove pathogens, metals, and organic contaminants (e.g., pesticides) but have not yet been shown to remove these toxic constituents at a safe enough efficiency to be reapplied as agricultural irrigation.[273]

Impacts

Agricultural wastewater from either crop land or meat processing plants in all regions of the country could utilize natural systems as low-cost passive treatment trains to remove organics, pathogens, and other toxic constituents. These treatment systems could be located adjacent to cropland for dual use as long-term storage ponds (see AOI R3) to facilitate decentralized agricultural reuse. Passive treatment systems such as engineered wetlands could also be viable treatment systems for agricultural reuse of low-salinity produced water in regions of Kern County, California or parts of Wyoming.

R5.

RESEARCH NEEDS:

- **Assess** the effectiveness of constituent removal via plant uptake or novel sorbents by determining the kinetics of these mechanisms and calculating the maximum accumulation capacity of each different type of plant or sorbent under varying natural conditions (TRL 3–4, 2–3 years).

- **Optimize** the area and topography of land used for wetland treatment systems by utilizing highly controlled hydraulics to maximize the kinetics of plant uptake mechanisms, novel sorbents, and physical degradation processes such as photolysis or sedimentation, thus minimizing the use of land that could otherwise be used for crops while still maximizing the potential for water treatment (TRL 2–3, 1–2 years).

- **Evaluate** engineered wetland systems that involve specific combinations and placement of plants to selectively remove constituents from wastewater before they negatively affect other plants downstream in the system. For example, salt-accumulating halophytes (i.e., hyperaccumulators) might be planted at the influent to selectively remove salts from the water that could negatively impact other plants in the system that are more suited to remove other metals (e.g., Cr), metalloids (e.g., As) or non-metals (e.g., Se).[274] Apply a modular system approach to develop engineered wetlands with optimal plant combinations and hydraulic properties that are resilient to changes in influent water quality and temperature (TRL 3–4, 2–3 years).

5.4. Intensified

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

I1.

Develop technologies for cost-effectively producing and managing low-volume, high-concentrated brines or other forms of desalination waste to avoid the use of dilution for their disposal.

Challenges

Brine management for meat and dairy processing operations such as cheese-making has proven a barrier to incorporating advanced desalination treatment technologies. Currently, settling tanks, evaporation ponds, and energy-intensive thermal treatments (e.g., submerged combustion) are used to create concentrated brine, which is reused in by-product processing in meat processing. The partially desalinated water is diluted in other wastewaters and discharged to urban treatment facilities or discharged into surface waters, where they are subject to water-quality-based effluent limits that vary with the quality of the receiving waters. Creating a treatment technology that can achieve either ZLD or produce high concentration brines with a cost-effective brine management plan, is essential to the sustainability of meat and dairy processing.[275,276] In other wastewaters, such as from tile drainage, the large-scale application of agricultural drainage desalination would produce an unmanageable amount of brine/salt, which could be contaminated with toxic constituents like Se.[277] Current practices of blending freshwater with agricultural drainage or brine resulting from the treatment of agricultural drainage uses large volumes of high-quality water to produce water that may not be economically feasible nor suitable for long-term irrigation use.[278]

Impacts

In beef processing, desalination of wastewater from brining processes can remove over 60 percent of total salt from the processing plant effluent, making it potentially available for reuse onsite or irrigation (See Section 3.3.2, Table 1). **Treating tile drainage to lower the SAR and remove other problematic constituents may make significant volumes of water available for irrigation in the arid Western United States.**

I1.

RESEARCH NEEDS:

- **Develop** ZLD systems that leverage low energy enhanced evaporation (e.g., wind-aided intensified evaporation [WAIV]) and renewable energy-driven brine treatment systems (e.g., enhanced solar thermal- or waste heat-driven membrane distillation) to lower the energy costs and increase the efficiency of ZLD technologies (TRL 3–4, 2–4 years).
- **Offset** by-product management costs by enabling the implementation of high-performance desalination or ZLD technologies, including through the selective valorization or reuse of dry by-products (e.g., reuse of recovered brine from desalination of hide brining wastewater in new hide brining processes, which are not food-grade and not sensitive to re-circulation of untreated organic constituents) (TRL 3–4, 4+ years).
- **Develop** technologies and modeling tools to ensure and predict the long-term stability of residuals (e.g., brine, sludge) from intensified brine management (TRL 2–3, 1–2 years).

12.

Establish systems to manage, recover, and create/improve the value of nutrients and residuals for fertilizers, Li (e.g., in produced water), Se (e.g., in tile drainage), proteins (e.g., in meat and dairy processing), salts, and other materials for new uses in circular economies.

Challenges

Achieving pipe parity for many alternative water sources will depend on the ability to recover valuable products that can be reused within agriculture or are marketable to industries. Numerous efforts have addressed issues of nutrient recovery (especially N and P) with precipitation, adsorption, electrochemical, electrocatalytic and biological processes,[279,280,281] but the thermodynamic and operational limitations of these processes for high-salinity waste streams is poorly understood. Removal and recovery of Se from brines provides the opportunity to reduce high concentrations of Se for waste disposal and a marketable product with economic benefits.[282,283,284,285,286] Reduction and recovery of Se in high-salinity wastes is challenging due to competition with common oxyanions present at higher concentrations (e.g., SO_4^{2-}), increased sensitivity of biological treatment systems, and scaling/fouling of catalysts, membranes, and electrodes. Moreover, high concentrations of Li in natural reservoirs and several man-made wastewater streams that are being considered for agricultural water reuse (e.g., produced water) can be leveraged to meet the growing demand for this industrially relevant element within the energy sector. To this end, current Li extraction processes are spatially and temporally inefficient, and high concentrations of other cations such as Na^+ and Mg^{2+} in these waters make the selective recovery of Li challenging from an operational perspective.[287,288]

Finally, proteins from meat processing represent an additional opportunity for addressing the economic challenges associated with treatment and disposal of waste from the food industry. Processes that have been considered for treatment of meat processing wastes include flotation, coagulation, adsorption, centrifugation, oxidation, biodegradation, ozonation, enzymatic treatments, and membrane technology, but few studies have considered the recovery of proteins as a parallel treatment objective.[289] Many of these processes are energy or chemically intensive, and there is a dearth of fundamental evaluation of the potential of these processes for protein recovery either alone or in combination with other processes. Developing more cost-effective technologies could offset operational costs and keep material in the circular economy.

Impacts

Reusing nutrients in agricultural wastewater, both from tile drainage and meat and dairy processing, for fertilizer is rarely implemented in practice due to high costs for treatment and managing the product streams. However, a cost-effective approach to this issue would solve multiple environmental issues and be a huge win for agriculture. In some cases, salts from meat and dairy processing wastewaters (e.g., sodium sulfate, sodium chloride, calcium sulfate) may be valorized within the Agriculture Sector or in nearby industries to offset the cost of treatment. At least one beef processing facility is already reusing recovered salts for new hide brining processes and displacing their salt expenses by over $300,000 a year (See Section 3.3.2, Table 2). Technologies with lower costs and/or better performance could expand the adoption of approaches like this.

12.

RESEARCH NEEDS:

- **Evaluate** the thermodynamics and kinetics of struvite precipitation from high-salinity waters or from a combination of high-nutrient and high-salinity waters, with a particular focus on the presence of impurities within the phases and the formation of phases that are less biologically available (e.g., hydroxyapatite) (see AOI M2) (TRL 3–4, 2–4 years).
- **Develop** biological or electrochemical treatment processes for reduction of Se oxyanions in high-salinity brines that can be coupled with Se (0) recovery (TRL 3–4, 2–4 years).
- **Evaluate** the use of a coupled electrosorption-electrocatalytic or other hybrid processes that provide pre-treatment for bulk salinity removal and subsequent processes (e.g., electrocoagulation) for resource recovery of ionic species (TRL 2–3, 1–3 years).
- **Develop** novel membranes that are capable of improving selectivity of Li^+ from brines that can be integrated with pre-and post-treatment processes for Li^+ recovery from brines (TRL 3–4, 2–4 years).
- **Develop** novel processes that couple enzymatic hydrolysis and separation of proteins from meat processing wastes (TRL 3–4, 3–5 years).[290]

13. Develop advanced modeling and in operando monitoring tools to understand precipitation, nucleation, crystallization, solute activity, and heat transfer in high-salinity waters to control scaling and intensify process design for brine treatment.

Challenges

Brines contain high levels of salts. Scaling caused by precipitation of sparingly soluble salts can significantly hinder the brine treatment and impair efficiency. Common scalants include $CaCO_3$, $CaSO_4$, $SrSO_4$, $BaSO_4$, CaF_2, $Ca_3(PO4)_2$, silica, and silicates. Scale formation involves a complex process from supersaturation, nucleation, crystallization, and precipitation. Crystallization starts after supersaturation and nucleation. There are two crystallization pathways: surface/heterogeneous crystallization on a surface or inside membrane pores; and bulk/homogeneous crystallization in a saturated solution.

As the constituents of brines vary drastically depending on their sources and processes used upstream, brine management is challenging because there is no universal method available. Using in operando monitoring tools and developing advanced geochemical models to predict chemical change and precipitation during brine management would significantly reduce cost. However, modeling brine streams is difficult due to the chemical complexity of brine and the need to characterize the chemical activity of individual chemical species under the high ionic strength and varying temperature and pressure conditions associated with treatment processes. The ability of current solution models to accurately predict precipitation kinetics under a wide range of temperature, pressure and solution compositions is limited.

New thermodynamic and kinetic models need to be developed based on water chemistry, temperature, pressure, and other considerations. The new models should be able to inform the design and operation of brine treatment processes.

Impacts

Scaling increases the costs and complicates operation and maintenance activities for desalination processes in the Agriculture Sector and beyond. Effectively addressing these issues would lower desalination costs across the United States.

13.

RESEARCH NEEDS:

- **Predict** scaling phases from supersaturation through precipitation over a range of temperatures and pressures relevant to process conditions or in the presence of other colloidal, organic, or biological species (TRL 3–4, 2–4 years).
- **Elucidate** mechanisms of homogeneous and heterogeneous nucleation and crystallization and their effect on fluid rheology (TRL 2–3, 2–4 years).
- **Develop** operando monitoring methods to characterize nucleation, crystallization, and molecular-to-macroscopic properties of hypersaline solutions at different operating conditions and varying brine chemistry (TRL 2–3, 3–5 years).
- **Develop** scale inhibition methods by understanding mechanisms of homogeneous and heterogeneous nucleation and crystallization (TRL 2–3, 2–4 years).
- **Simulate** thermodynamic and transport properties of concentrated electrolytes in multicomponent, multiphase systems, including the effects of various organic components on mineral scaling and other thermodynamic properties such as the induction time for the precipitation of mineral scales (TRL 3–4, 3–5 years).
- **Model** co-precipitation and sorption of toxic contaminants during crystallization and precipitation to ensure regulatory compliance (TRL 3–4, 2–4 years).

5.5. Modular

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

M1. Develop high-rate and high-recovery desalination processes (e.g., >98 percent) for agricultural applications using a range of approaches such as electrodialysis.

Challenges

Desalination of nontraditional water such as brackish water and wastewater requires low-cost, high-rate, and high-recovery technologies for agricultural applications with minimal waste disposal. MD, closed-circuit reverse osmosis (CCRO), ED, EDR, monovalent SED, and osmotic assisted membranes are identified as possible desalination processes for agriculture applications such as greenhouses.

ED is an electrically driven membrane desalination process suitable for partial desalination of wastewater at high water recovery and separation rates for agricultural applications. EDR is similar to ED, except for the periodic reversal of current direction for retarding scaling and fouling on membrane surfaces and maximizing desalting performance. SED uses monovalent permselective membranes to selectively remove sodium and chloride ions while preserving most of the hardness ions as fertilizer for plant growth.[291,292,293] The SED process can achieve high recovery of water with high hardness and sulfate content by keeping the divalent ions away from the concentrate stream. Under partial desalination for agricultural irrigation, SED could operate at high-rate and high-water recovery (e.g., >98 percent) with effective control of mineral scaling and retain calcium and magnesium needed for plant growth.[294]

The selection of desalination technologies should consider the capital and operational costs, energy efficiency, reduced costs for concentrate disposal, and savings from recovery of additional water and fertilizer from using selective desalination technologies. As scaling and fouling are the major barriers in implementing high water recovery processes, new process design with real-time monitoring would facilitate high water recovery in existing membrane systems.

Impacts

Using saline water sources for agricultural irrigation requires partial desalination and selective separation of salts (e.g., removing Na^+ but leaving Mg^{2+} and Ca^{2+}). Developing selective desalination processes that operate at a high rate with high water recovery could reduce the costs of reusing brackish water and municipal wastewater for irrigation by 20–30 percent[295] compared to conventional RO and may allow these sources to achieve pipe parity for higher value crops in water-scarce regions.[296]

M1.

RESEARCH NEEDS:

- **Develop** low-cost and high-recovery (>98 percent) desalination technologies (TRL 3–4, 2–4 years).
- **Develop** selective technologies that remove unwanted constituents (e.g., Na^+, Cl^-, B, Se) but retain fertilizers in the treated water (e.g., K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, NO_3^-, and PO_4^{3-}) (TRL 2–4, 2–4 years).
- **Develop** a smart integrated membrane system with autonomous, self-adaptive operation to monitor and control mineral scaling and fouling (TRL 3–4, 3–5 years).

M2. Create a hybrid system combining wastewater treatment with onsite production of fertilizers (e.g., osmotic membrane, electrochemical processes, ion exchange, pervaporation).

Challenges

Current fertilizer production is energy-intensive and heavily relies on the finite mineral resources.[297] Economically mineable deposits of phosphate rock are depleting at an alarming rate.[298] On the other hand, substantial fossil energy is required for removal of N species from wastewater as N_2 gas by nitrification and denitrification. Recovery of nutrients from waste streams such as municipal wastewater, agricultural wastewater, and centrate from anaerobic digesters provides a promising strategy for more sustainable wastewater treatment and agriculture.

Struvite ($MgNH_4PO_4 \cdot 6H_2O$) precipitation has been commercially implemented as the most promising technology to recover nutrients in wastewater, anaerobically digested sludge, and urine. However, nutrient recovery from wastewater as struvite is limited by the P concentration in wastewater (typically 6-10 mg/L in municipal wastewater, and up to 60 mg/L in digested sludge supernatant). During struvite precipitation, toxic heavy metals and organic contaminants in wastewater may also co-precipitate or adsorb to struvite, compromising the quality of fertilizer for safe agricultural uses.

Impacts

A cost-effective hybrid treatment system would facilitate decentralized reuse of all agricultural wastewater.

M2.

RESEARCH NEEDS:

- **Enhance** nutrient recovery efficiency, selectivity, and modularity of chemical precipitation and avoid the co-precipitation of organics and heavy metals to struvite (TRL 4, 1–2 years).
- **Understand** the adsorption kinetics and mechanisms to develop low-cost, fast-uptake, selective, and regenerable adsorption materials, (e.g., ion exchange resins, ion exchange membranes, zeolite, bentonite, and hydrogels) (TRL 2–4, 2–4 years).
- **Develop** novel combinations of nutrient recovery processes (e.g., ED-RO, ED-struvite precipitation, FO-RO, RO-MD, adsorption-hollow fiber membrane contactor, electrochemical processes, and gas permeable membrane). The novel system integration and optimization of recovery processes can substantially improve nutrient recovery efficiency, diversify nutrient products with high concentration and quality (e.g., 2M ammonia, NH_4NO_3, $(NH_4)_2(HPO_4)$), and generate desired fertilizers for in situ agricultural uses (TRL 3–4, 3–5 years).

M3.

Develop small-scale modular desalination technologies that operate on electricity, renewable energy, or waste heat to remove salts and proteins.

Challenges

Advanced desalination technologies are common in large-scale industrial settings. Small scale desalination technologies, however, are implemented with much less frequency. For desalination of brackish water and agricultural wastewaters modularized, small-scale technologies, such as those used for the removal of salts and proteins, need to be designed, similar to those found in wastewater from meat and dairy processing.[299] This is especially true where highly concentrated brines are generated in low volumes, which are typically diluted and then treated elsewhere due to the lack of commercial availability of small-scale equipment. Small-scale desalination technology could take advantage of waste heat/biofuels (produced during other treatment processes) to remove salts for reuse and produce a low TDS effluent.

Impacts

Low-volume, high-TDS flows that are conducive to decentralized, modular treatment are present in cheese and beef processing systems. These cumulatively produce 2 trillion liters (530 billion gallons) of wastewater that could potentially be treated and reused onsite or for irrigation nearby (See Section 3.1, Figure 6). Developing cost-effective and small-scale treatment processes could reduce the cost for the transportation of saline drainage water to treatment facilities far from the source of water and/or the irrigation end use. Small-scale technologies can also reduce costs and improve performance in other sectors.

M3.

RESEARCH NEEDS:

- **Implement** desalination technologies for low-volume, high-salinity flows in meat processing (e.g., wastewater from hide brining) (TRL 4+, 2–4 years).
- **Develop** effective and efficient low-cost transportation methods for selectively treated wastewaters and treatment by-products (e.g., design of low-cost, wide range pipelines for application of meat processing wastewater, without N and P removal, for irrigation applications) (TRL 2–3, 1–2 years).

M4. Develop and integrate beneficial modular designs in engineered natural treatment systems (e.g., modularity with natural systems.)

Challenges

Natural treatment systems, like constructed wetlands, have the potential of treating nontraditional water sources and meeting pipe-parity goals through a treatment system that utilizes physical and biological wetland processes to remove constituents.[300] These natural biofiltration treatment systems have low energy and maintenance costs and can provide active storage of water for reuse during dry periods.[301] Engineered constructed wetlands have been used to treat a variety of wastewaters, but there is a need for modular and climate-resilient wetland designs that can achieve higher removal efficiencies. There is a need for treatment wetlands with optimal hydraulics (e.g., residence time, velocity profile) that can meet target effluent goals for use in the Agriculture Sector. Wastewater from nontraditional sources contain high levels of a broad range of constituents and would require a treatment wetland that is designed for its specific range of constituents.[302] Continued use of natural treatment processes can result in accumulation of toxic constituents in soil and plant tissue, leading to decreased constituent removal, decreased effluent water quality, retiring of the land, and potential environmental harm.[303,304,305] Contact between untreated water and animals is a concern and challenge when employing natural treatment processes because contact with contaminated water can cause toxicity problems, deformities, and death in fish, waterfowl, and other wildlife.[306,307] Water temperature presents another challenge with using natural treatment systems in different regions. Water temperature can reduce the function of natural treatment processes, preventing regions with colder temperatures from implementing this type of treatment.[308] As industries consider the implementation of natural treatments, there is a need for a modular approach to the design to produce a treatment process that is adaptable to variations in the influent water quality, water temperature changes, and agricultural end-use needs.

Impacts

Natural systems (e.g., constructed wetlands, grassland buffers) can be refined to provide a low-cost and low-maintenance treatment option applicable across the United States in agricultural settings and other rural applications. Plants can be identified to target constituents of concern (e.g., Se, B, and salts in the Western United States; nutrients in the Midwest and Eastern States). When advanced treatment of tile drainage is required, natural systems could provide pre-treatment and remove constituents near the source before the water is transported to a treatment facility.

M4.

RESEARCH NEEDS:

- **Develop** a modular approach to natural treatment including the appropriate plant and microbial species, hydraulic residence time, directed flow, and soil/substrate to remove specific constituents that are associated with the nontraditional water source (TRL 3–4, 2 years).
- **Design** engineering wetlands with self-cleaning mechanisms to reduce constituent accumulation and toxicity to extend the lifetime of the treatment system (TRL 2–4, 3 years).
- **Develop** modular design aspects for constructed wetlands that can be used for water sources that have wide variations in water quality, require selective removal of toxic constituents, and can be used in regions with distinct temperature changes (TRL 3–4, 3 years).
- **Investigate** the use of pre-treatment processes to improve influent water quality; additionally, investigate the use of post-treatment processes to polish water after the main natural treatment process, and to recover valuable products that can be profitably recycled to agriculture or other beneficial uses (TRL 2–4, 2 years).

5.6. Electrified

Electrifying Water Treatment Processes and Facilitating Clean Grid Integration

E1. **Develop innovative materials for advanced electro-membranes and electrocatalytic and bio-electrochemical systems that can be used for pretreatment (e.g., chemical-free scaling and fouling control, pH adjustment), treatment (i.e., removal of contaminants), and posttreatment (e.g., UV-LED AOPs) to improve system performance and reduce costs.**

Challenges

Advance electrocatalytic oxidation/reduction processes for removal (degradation) of contaminants. In recent years, numerous studies related to electrocatalytic processes (electro-oxidation and electro-reduction) have focused on advancing the performance of catalysts, particularly by assessing different electrode materials, which include boron doped diamond (BDD),[309] platinum, metal oxides (e.g., PbO_2, SnO_2), metal oxide composites (e.g., dimensionally stable anodes (DSA)), and carbon-based materials (e.g., carbon fibers/tubes,[310] and graphite[311]). The pollutant removal performance of catalysts highly depends on the electrode properties and operational parameters, such as oxygen overpotential, conductivity, pH, and background current. Despite achieving high pollutant removal efficiency, the large-scale applications of current electrocatalytic processes have been limited by high cost, instability, and relatively high energy intensity.

Advance electro-membranes with fouling control. Recently, electro-membrane processes such as Electro/Capacitive Deionization (EDI/CDI), ED, EDR, and bipolar membrane electrodialysis (EDBM)[312,313] have gained attraction for treating nontraditional water sources (e.g., brackish water). These technologies offer several advantages, including high separation efficiency, low energy consumption, and modularization.[314,315] Fouling and scaling have limited the broader acceptance of electro-membrane separation for treating nontraditional water sources (e.g., brackish water). Studies have mainly focused on altering membrane properties, such as hydrophilicity and permselectivity. However, stability, operational costs, and capital costs remain obstacles for large-scale applications.

Challenges, cont.

Advance electrocoagulation systems for pretreatment and treatment. Electrocoagulation, which generates coagulants in situ via electrolytic oxidation of an anode has gained much interest recently. Such a process is inherently modular and portable, is suitable for distributed treatment, reduces the need for external chemical addition, and has been shown to remove contaminants of interest in agricultural water reuse (e.g., Cr (VI),[316,317] As (III),[318] B,[319] other trace metals,[320] NOM.)[321] Electrocoagulation (and its sister process electroflotation) is also effective for membrane pretreatment.[322] However, a poor understanding of its capabilities and limitations, including technical, design, and operational issues, has given it a bad name and hampered its implementation.

Impacts

Electrified treatment technologies can improve the traditional technologies by offering greater efficiency and smarter solutions for energy utilization and chemical reduction. Electrified tile drainage treatment systems provide the possibility to transform nutrients and carbon sources from complex and unavailable forms to more biologically available forms, which can be utilized directly for agricultural irrigation, reducing treatment needs and fertilizer purchases.

E1.

RESEARCH NEEDS:

Advance electrocatalytic oxidation/reduction processes for removal (degradation) of contaminants.

- **Develop** novel, high-performance, cost-efficient, and robust electrode materials (i.e., materials with high specific surface area, high electrical conductivity, long-term stability) to target contaminants such as PFAS, nitrate, and Se in practical applications (TRL 3–4, 3–5 years).
- **Optimize** the design of electrocatalytic reactors by improving the electric energy efficiency (e.g., reactors that remove H_2 gas-to-water mass transfer while simultaneously minimizing boundary layer mass transfer resistance, three-dimensional electrochemical reactors, reactors that increase surface area and reduce mass transfer distances such as three-dimensional electrochemical processes[323]) (TRL 3–4, 2–4 years).
- **Create** a hybrid system combining electrocatalysis with other treatment technologies (e.g., membrane filtration, photocatalysis, biological treatment, electrosorption) to achieve maximum utilization of the electrocatalytic processes with no (or minimum) chemical input, less energy intensity, and no (or minimal) generation of chemical waste byproduct (TRL 4+, 4+ years).
- **Design** stable, modular, cost-efficient electrode materials for in-situ generation of oxidants. The materials are expected to provide enhanced yield of oxidants from both cathodic or anodic pathways with high selectivity and current density[324] (TRL 3–4, 2–4 years).

Advance electro-membranes with fouling control.

- **Develop** novel electrically conducting membranes that can alter pH at the membrane surface (e.g., for B removal) (TRL 2–3, 1–3 years).
- **Design** low-cost, selective, and resilient membrane materials that focus on pore geometry to prevent irreversible fouling (e.g., intrapore blocking) and facilitate cleaning (TRL 2–3, 2–4 years).
- **Design** smart electrocatalytic systems that autonomously monitor fouling and scaling and clean membranes (TRL 2–3, 3–4 years).
- **Develop** electrocatalytic and membrane hybrid systems to achieve contaminant degradation (or transformation or removal), biofouling control, and separation (TRL 3–4, 3–5 years).
- **Design** advanced pre-treatment processes to achieve efficient separation with no (or minimum) chemical input, less energy intensity, and no (or minimal) generation of chemical waste byproducts (TRL 3–4, 3–5 years).
- **Develop** novel selective electro-membrane processes[325] and models[326] of perm-selectivity of membranes focusing on contaminants of importance in agricultural water reuse (e.g., nitrate, Cr (VI), Se (VI), As (III)) (TRL 3–4, 3–5 years).

Advance electrocoagulation systems for pretreatment and treatment.

- **Develop** performance models to improve our fundamental understanding of electrocoagulation. Familiarity with its pros and cons will allow better operation and design, eventually making it cost-effective and generating more interest from stakeholders (TRL 2–3, 2–4 years).
- **Design** efficient electrocoagulation systems by innovation in the synthesis of electrode materials, optimization in operational conditions (e.g., alternating current), and an understanding of the role of water quality) on electrode behavior (TRL 3–4, 3–5 years).
- **Establish** hybrid electrocoagulation-membrane processes to facilitate industry acceptance (TRL 3–4, 4+ years).

E2.

Integrate renewable/alternative energy with electrified desalination and related processes for remote/farm location. Develop techno-economic models to quantify the synergies between these two systems as well as the benefits gained in stability, reliability, and flexibility derived from electrification.

Challenges

Electrified desalination and related processes in remote farm locations need to receive electricity from somewhere to provide the desired functionality. Since power is such a critical part of the facilities operations, it can be both a logistical and economic challenge to provide this resource in extraordinary locations. The use of renewable energy technologies and other alternative sources, such as solar, wind, hydro, geothermal, and biomass, are great candidates to meet this need because of their versatility in this space. However, two of the main challenges to their adoption is their dynamic, less predictable nature and relatively expensive capital and installation costs (and accompanying long payback periods). Many of the existing processes in this domain were designed and are operated under the assumptions of steady-state behavior, perhaps because of its simplicity. However, more modern and advanced approaches are needed to reflect and realize the potential of a complete electrified water treatment system.

Impacts

The topographically complex nature of agricultural operations and farms is inherent at all levels of investigation. Understanding the techno-economics and integrating the appropriate energy sources improve the efficacy of certain desalination and water reuse technologies at the sectoral and regional level. This AOI may also contribute methods and technologies for integrating alternative, power-intensive technologies that need to be deployed at distributed locations, broadening its reach.

E2.

RESEARCH NEEDS:

- **Advance** understanding and implementation of integrated, multidisciplinary modeling, analysis, and optimization of dynamic and controlled systems (TRL 2–3, 1–3 years).
- **Develop** increasingly dynamic systems and finer operational control to improve performance and reliability and meet other societal needs (TRL 2–3, 1–3 years).
- **Develop** techno-economic models, integrated analysis frameworks, and design studies to enable identification of the means and mechanisms for exploiting the synergies between the temporal variations in the cost of electricity, energy sources, and operational needs (TRL 2–3, 2–4 years).
- **Develop** tailored assessments for reduced operating costs for the diversity of remote/farm locations that may be interested in these technology solutions (TRL 3–4, 1–3 years).

E3.

Develop technologies to concentrate contaminants for more efficient treatment (e.g., smaller volumes, higher removal rates) by electrochemical and electrocatalytic processes.

Challenges

Electrochemical and electrocatalytic technologies are powerful means to degrade recalcitrant contaminants for water and wastewater treatment. But many contaminants in the wastewater, such as pharmaceuticals and PFAS, are present at trace concentrations. These low concentrations result in slow kinetics of destructive reactions, decreasing the efficiency and increasing treatment cost of electrochemical and electrocatalytic technologies. Concentrating contaminants prior to electrochemical and electrocatalytic treatment, therefore, is pivotal to improving the kinetics of contaminant removal and achieving effective water and wastewater treatment at substantially reduced costs. However, other constituents in the feedwater are also concentrated along with the targeted contaminants. High concentrations of interfering species like inorganic ions and NOM could result in unintended outcomes, such as decreasing treatment performance or forming toxic by-products.

Impacts

For any contaminants that need electric destructive technologies, concentrating the contaminants is important to reduce the cost because kinetics are slow at dilute concentrations. Coupling concentrating technologies with contaminant degradation technology is the key to reduce treatment cost in the Agriculture Sector and beyond.

E3.

RESEARCH NEEDS:

- **Obtain** mechanistic understanding upon the roles of co-existing constituents in regulating the kinetics of electrochemical and electrocatalytic treatment (TRL 2, 1–3 years).
- **Understand** the potential of toxic byproduct formation when treating concentrated feedwater with electrochemical and electrocatalytic processes (TRL 2–3, 2–4 years).
- **Develop** precise separation technologies that selectively concentrate the targeted contaminants but not interfering constituents (TRL 2–3, 2–4 years).
- **Perform** TEA and LCA to understand the economic and environmental benefits of applying pre-concentrating technologies prior to electrochemical and electrocatalysis processes (TRL 3–4, 2–4 years).

E4. Improve energy efficiency by waste heat recovery and systems optimization of electrified driven processes (e.g., recover heat from boiler water or engines used in meat and dairy processing).

Challenges

Wastewater treatment systems, specifically desalination technologies, can be very energy-intensive. Electrical systems, such as MVR, require large amounts of electrical energy to heat water. Similarly, thermal systems, such as evaporation or some membrane technologies, also treat water by heating it. In both these cases, the amount of energy needed from electricity or thermal energy sources (i.e., burning fuels) could be reduced with waste heat recovery. Recovery of waste heat in meat and dairy processing could come from engines, pumps, hydraulics systems, boilers, and various processing operations.[327,328] Collection of waste heat could even come from the warm wastewater streams. This waste energy could be used to pre-heat wastewaters entering treatment systems, requiring less energy in the treatment technology to heat water for treatment.

Impacts

Desalination processes are energy intensive. Energy requirements in meat and dairy processing, as well as in other sectors, can be reduced by incorporating waste heat recovery.

E4. RESEARCH NEEDS:

- **Implement** waste heat recovery systems in energy-intensive wastewater desalination technologies such as MVR or MD to reduce the energy demand of effective high-performance desalination (TRL 4+, 2–4 years).

5.7. Further Consideration for Water Use in Agriculture

When evaluating alternative water sources for use in agriculture, one of the largest barriers to adoption is the price of water. Currently, fresh water used for irrigation and other agricultural users, such as feedlots, dairies, and meat and dairy processing facilities, costs as low as $0.007/m³ ($8.64/acre-foot; $0.026 kilogallons).[329]

Implementation of new water sources is typically much more expensive than current options. On the other hand, in water-scarce regions that do not have enough fresh water for agricultural needs, additional water would be useful to the production and processing of agricultural goods, with affordable water prices necessary for profitable operation. Therefore, when evaluating water as a source for agricultural purposes, the water must be as economically viable as possible for agricultural users.

The costs for new water sources (e.g., treated tile drainage, treated municipal wastewater , treated wastewater from meat and dairy processing facilities, treated produced water from oil and natural gas extraction) are driven by the technology costs associated with the treatment of water. Many source water generators are burdened with treatment costs. Treatment systems, especially desalination systems, are expensive both to implement (capital expenses [CAPEX]), especially in small-scale settings such as for tile drainage desalination) and operate (especially in waters with complex combinations of constituents, such as in meat and dairy processing). The combination of both low CAPEX and operating expenses (OPEX) of treatment systems is necessary for viable treatment systems to be implemented for water treatment with the goal of reuse within agriculture.

Furthermore, due to environmental regulations, costs for wastewater management are unavoidable. Because regulations govern water quality and product safety, these wastewaters must be treated, no matter if for reuse within agriculture or for discharge. For example, extensive treatment is used in meat processing to meet USDA and internal product safety requirements, and discharges from these and municipal wastewater facilities are governed by the Clean Water Act, as administered by EPA.

Using the wastewater for agricultural applications may provide these facilities with options for new treatment systems that provide water at the quality required for reuse rather than discharge. For example, removal of N and P from wastewaters is not necessary for irrigation applications because of their soil fertilizer properties, which is an added benefit to the source facility because it diminishes requirements for constituent removal.

Another by-product of water treatment may be biogas from digestion of organics, and it is likely that more opportunities for efficient design and utilization of treatment operations and by-products exist. Improving the economic viability of treatment systems that can treat to the level needed for agricultural applications could enable a transition to other advanced treatment technologies.

6. NEXT STEPS

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

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

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

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

Appendix A: Acronyms

AI	Artificial Intelligence
A-PRIME	Autonomous, Precise, Resilient, Intensified, Modular, and Electrified – NAWI R&D focus area
AMO	Advanced Manufacturing Office
AOI	Areas of Interest
AOP	Advanced oxidation process
As	Arsenic
B	Boron
BDD	Boron doped diamond
BGD	Billion gallons per day
BGW	Brackish groundwater
BLD	billions of liters per day
BOD	biological oxygen demand
BWRO	brackish water reverse osmosis
Ca	Calcium
CAPEX	Capital expenses
CCRO	closed-circuit reverse osmosis
Cd	Cadmium
CEC	Contaminants of emerging concern
CO_2	Carbon dioxide
COD	chemical oxygen demand
CSIP	Castroville Seawater Intrusion Project
Cl	Chlorine
Cr	Chromium
Cu	Copper

DAF	dissolved air flotation
DOE	U.S. Department of Energy
DSA	dimensionally stable anodes
ED	Electrodialysis
EDBM	bipolar membrane electrodialysis
EDCs	endocrine-disrupting chemicals
EDI/CDI	electro/capacitive deionization
EDR	electrodialysis reversal
EPA	U.S. Environmental Protection Agency
Fe	Iron
FO	forward osmosis
ft	feet
GPD	gallons per day
H_2O_2	Hydrogen peroxide
HACCP	Hazard Analysis Critical Control Point
HDPE	high-density polyethylene
IFDM	Integrated on-farm drainage management
IoT	Internet of Things
IWMS	Irrigation and Water Management Survey
K	Potassium
kWh/ m^3	kilo-Watt-hour per cubic meter
LCA	Life cycle analysis
LCOE	Levelized cost of electricity
LCOW	Levelized cost of water
LED	Light emitting diode
Li	Lithium

LW	Live Weight
MBR	membrane bioreactors
MD	Membrane distillation
Mg	Magnesium
mg/L	Milligrams per liter
mi^3	Cubic mile
MJ/ton	Mega-Joule per ton
Mn	Manganese
mS/cm	millisiemens per centimeter
MVC	mechanical vapor compression
MVR	mechanical vapor recompression
N	Nitrogen
Na	Sodium
NAWI	National Alliance for Water Innovation Hub
NF	nanofiltration
NMDG	N-methyl-D-glucamine (1-amino-1-deoxy-D-glucitol)
NO_3	Nitrate
NOM	natural organic matter
NORM	Naturally Occurring Radioactive Materials
NPDES	National Pollutant Discharge Elimination System
O&G	oil and gas
O&M	operations and maintenance
OPEX	operating expenses
P	Phosphorus
PAHs	polycyclic aromatic hydrocarbons

Pb	Lead
PCB	polychlorinated biphenyls
PCN	polychlorinated naphthalenes
PFAS	Per- and polyfluoroalkyl substances
pH	Potential of hydrogen to specify the acid or base strengths
PO_4	Phosphate
PPCPs	Pharmaceuticals and personal care products
PRIMA	Power, Resource Extraction, Industry, Municipal, Agriculture End-Use Sector focus for NAWI
PVC	polyvinyl chloride
PW	produced water
R&D	Research and Development
RAC	Research Advisory Council
RFP	Requests for projects
RO	Reverse osmosis
SAR	Sodium Adsorption Ratio
SCADA	Supervisory control and data acquisition
Se	Selenium
SED	Selective electrodialysis
SiO_2	Silicon dioxide
SLDTP	San Luis Demonstration Treatment Plant
SO_4	Sulfate
SSOP	Sanitation Standard Operating Procedure
SVRP	Salinas Valley Reclamation Project
SWRO	seawater reverse osmosis
TCE	trichloroethylene

TDS	Total Dissolved Solids
TEA	Technoeconomic analysis
TMWW	treated municipal wastewater
TRL	Technology readiness level
TSS	total suspended solids
UF	ultra-filtration
U.S.	United States
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UV	Ultraviolet
v/v	volume per volume
Water-TAP3	Water Technoeconomic Assessment Pipe-Parity Platform
WAIV	wind-aided intensified evaporation
WWTP	Wastewater treatment plants
ZLD	Zero-liquid discharge
Zn	Zinc

Appendix B: NAWI A-PRIME Expanded Descriptions

Autonomous:

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

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

Precise:

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

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

Resilient:

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

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

Intensified:

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

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

Modular:

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

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

Electrified:

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

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

Appendix C: DOE Water Hub Development Background

DOE's Water Security Grand Challenge is a White House-initiated, DOE-led framework to advance transformational technology and innovation to meet the needs for safe and affordable water and help secure the nation's water supplies. Using a coordinated suite of prizes, competitions, early-stage research and development funding opportunities, critical partnerships, and other programs, the Water Security Grand Challenge sets the following goals for the United States to reach by 2030:[330]

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

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

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

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

Appendix D: Roadmap Teams

Cartography Team

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

Core NAWI Teams

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

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

Broader Teams

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

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

Appendix E: Development of the NAWI Agriculture Sector Technology Roadmap

Data Collection Process

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

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

Activities Prior to the Technology Roadmapping Workshop

Online Survey

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

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

Subject Matter Expert Interviews

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

Core and Broader Team Brainstorming

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

Technology Roadmapping Workshop

Workshop Purpose

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

Workshop Format

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

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

Workshop Outputs

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

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

Preparation of the NAWI Technology Roadmaps

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

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Appendix G: **References**

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