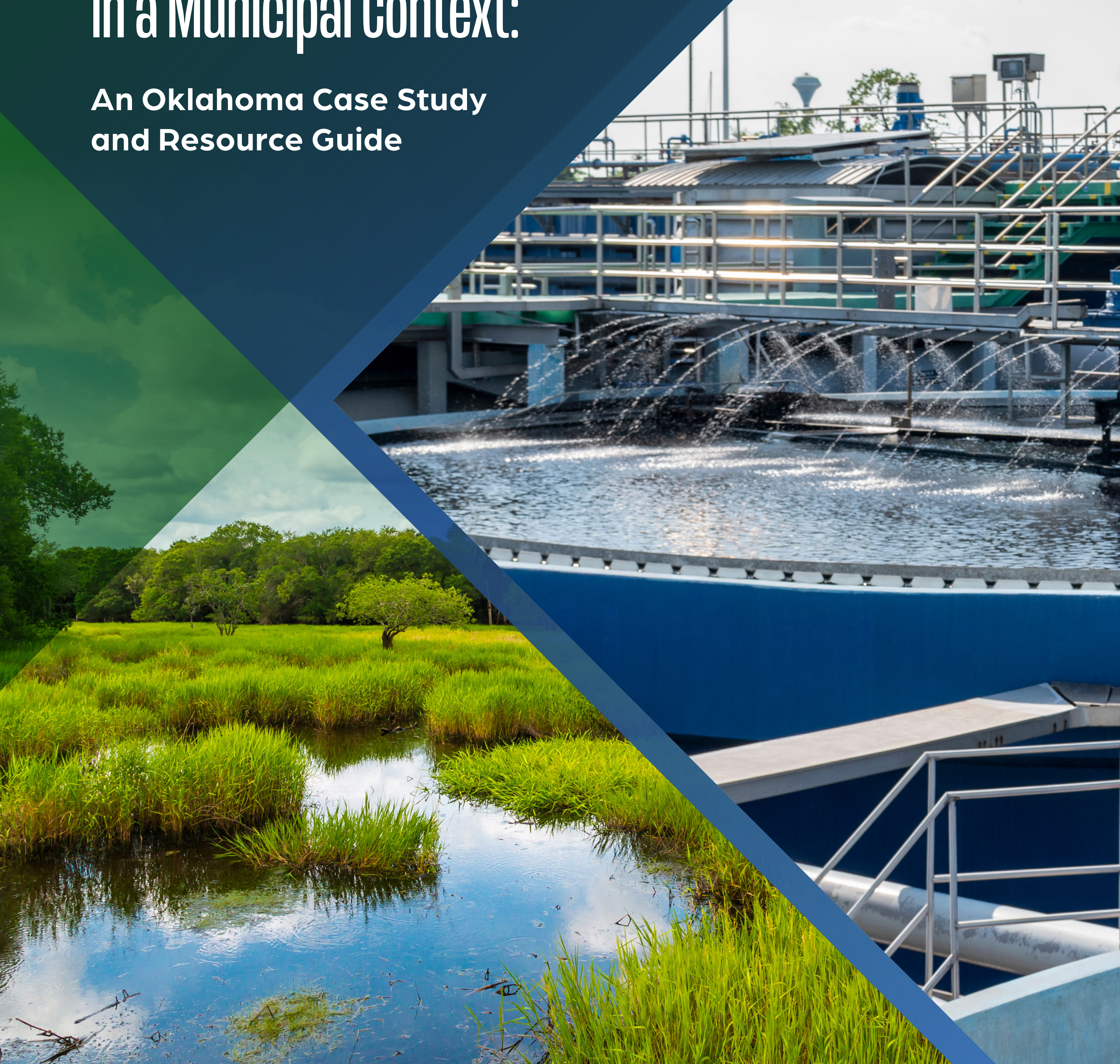
CHAPTER 7

Exploration of Hybrid Treatment and Reuse Alternatives for Wastewater and Stormwater in a Municipal Context:

An Oklahoma Case Study and Resource Guide



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CHAPTER 7

Exploration of Hybrid Treatment and Reuse Alternatives for Wastewater and Stormwater in a Municipal Context: An Oklahoma Case Study and Resource Guide

In Summer 2020, Oklahoma received a National Science Foundation *Established Program to Stimulate Competitive Research* (EPSCoR) award to conduct research and collaborate with practitioners to address particularly complex issues, referred to as wicked problems, facing Oklahoma in the areas of variable and marginal quality water supplies, land use, and infrastructure as they are impacted by changing seasonal and subseasonal weather patterns. The premise for this *Socially Sustainable Solutions for Water, Carbon and Infrastructure Resilience in Oklahoma* project, dubbed the "S3OK" project, is that socially sustainable solutions to complex societal problems will be found at the intersections of related but distinct problem areas, where diverse stakeholders can find agreement because the array of issues cuts across the usual narratives that frame social conflict. The project emphasized not just research, but systematic and iterative engagement between key stakeholders, the public, and researchers to identify convergent solutions in these key areas. The funded S3OK project created the foundation for the research and collaboration outlined in the case study and resource guide below.

To ensure iterative engagement between key stakeholders and scientists, the S3OK project team recruited nearly 70 distinguished practitioners from around Oklahoma to advise the project across its science focus areas; a significant subset of these practitioners (approximately 35) represented the water sector, including municipal officials, state officials, federal officials, private firms, nonprofit associations, and more. This practitioner group – the Opinion Leader Advisory Network (OLAN) – was instrumental in guiding the researchers' focus to ensure that the science undertaken through the project was highly relevant to and needed by Oklahomans, and such that this science could be applied directly to the challenges currently faced by Oklahoma's water sector. Partners in this working group included researchers from the University of Oklahoma (OU), Oklahoma State University (OSU), Garver, the City of Norman, United States Bureau of Reclamation (USBR), Oklahoma Water Resources Board, Oklahoma Rural Water Association, Central Oklahoma Master Conservancy District, Southwestern Oklahoma State University (SWOSU), Chickasaw Nation, Cherokee Nation, Oklahoma Department of Environmental Quality (OK DEQ), Carollo Engineers, and numerous others.

Rationale for Exploration of Novel Water Treatment and Reuse Approaches

Through the S3OK opportunity, researchers and OLAN members consistently collaborated over a five-year period to define and discuss wicked problems of mutual high priority, and select specific topic areas to work on in-depth in a 15-month working group format. Within this context, S3OK researchers and OLAN members collaboratively selected to explore the topic of *Novel Hybrid Treatment and Reuse Options for Stormwater and Municipal Wastewater*. The group specifically delineated the concept of hybrid systems as a high priority for further exploration, as both engineered and natural systems were seen as having the potential for complementary benefits in a paired approach. In particular, S3OK presented an opportunity to advance work that explores the possibility of integrating constructed treatment wetlands and other natural infrastructure that can work in concert with traditional engineering approaches, not only to help address water quality needs, but also to provide additional benefits to an indirect potable reuse (IPR) system. Through IPR, highly treated municipal wastewater is discharged into a receiving surface or groundwater source to augment the water supply for later use as a drinking water source.

The S3OK work is particularly fitting in the Oklahoma context, given that, under the Water for 2060 Act in 2012, Oklahoma became the first state to establish a goal of consuming no more freshwater in 2060 than it did in 2010. Further, the *2012 Update of the Oklahoma Comprehensive Water Plan* forecasted the possibility of future water shortages and therefore, the plan recommended that agencies should collaborate with entities that are exploring initiatives that include water reuse.[1] Additionally, Oklahoma's communities are not only facing challenges with their water supply, but also face increasing challenges in meeting new water quality regulations. The US EPA's 2024 additions to the National Primary Drinking Water Regulation (NPDWR) for six perfluoroalkyl and polyfluoroalkyl substances (PFAS) will soon require all drinking water systems to measure and remove these identified chemicals.[2] Additionally, each community has unique contexts for nutrient loads and other localized contaminants that must be addressed.

The treatment wetlands work undertaken through S3OK originally focused on municipal wastewater. However, because of synergies with a U.S. Bureau of Reclamation scoping study, *Integrating Engineered Treatment Wetlands into Water Reuse and Stormwater Management to Enhance Water Supply and Multi-Purpose Benefits,*[3] this study evolved and evaluated the proposed research questions of interest for a City of Norman project that incorporates wetlands into a stormwater and wastewater treatment design.

To advance exploration of the potential to implement hybrid treatment approaches for wastewater and stormwater treatment and reuse, the working group members outlined several goals:

- **Explore Hybrid Treatment Alternatives**: Focus on exploring various hybrid, nature-based, and active treatment options to evaluate their feasibility and potential effectiveness in addressing water treatment and supply challenges.
- **Seek Progress Towards Implementation**: Prioritize actions to promote demonstrable progress towards implementation, including both treatment wetlands and active treatment approaches, moving beyond laboratory settings to pilot opportunities. Seek opportunities to tie the success of pilot projects to future funding possibilities.
- **Develop Tangible Products for Community Guidance**: Utilize the S3OK opportunity to develop tangible products such as case studies or resource guides to facilitate action by other communities interested in pursuing treatment wetlands, innovative stormwater best management practices, or hybrid treatment trains.

Case Study: City of Norman

This case study focuses on the City of Norman, an Oklahoma municipality. It presents information and results from each of the S3OK Novel Hybrid Treatment and Reuse Options for Stormwater and Municipal Wastewater working group's goals. The study looks at how Norman is exploring water reuse and hybrid approaches to indirect potable reuse (IPR) to address challenges related to both water quality and quantity.

In presenting this case study, S3OK collaborators aim to showcase the progress made by the City of Norman and its partners toward integrating wetlands, along with other natural and engineered options, into an IPR project. The focus is on lessons learned and barriers overcome regarding the role of treatment wetlands as part of a hybrid system for water treatment and reuse. This case study also serves as an example for other municipalities considering water reuse strategies to manage or augment water supplies in the face of increasing demands or erratic availability due to extreme weather events, and to provide new tools for addressing water quality. While the water profile and conditions/challenges of focus for this Norman project may be most similar to other Central Oklahoma municipalities, the collaborative team intends for this case study to be useful to utilities outside Oklahoma's central region as well.

In presenting the additional considerations and resources for communities to consider, working group members also intend to offer complementary technical advances that were explored for Norman. Though developed with Norman in mind, these technical advances can be considered by other municipalities as well, as potential approaches to water treatment and reuse challenges. They can also bring awareness to future needed work and be used as a springboard to discuss important considerations to account for when undertaking significant projects. The working group acknowledges the significant undertaking of addressing water treatment and reuse projects, not only choosing effective and cost-conscious approaches, but also working within ever-evolving regulatory frameworks and implementing and communicating solutions that can garner adequate public support. To that end, the resource guide includes information to better understand the Oklahoma public's perceptions of water treatment and reuse approaches, as well as a discussion of common regulatory requirements pertinent to water quality standards, water management, and other environmental quality needs.

Finally, in an effort to make this case study and resource guide as broadly applicable as possible, the S3OK working group conceptualized a hypothetical Treatment and Reuse Diagram, shown in **Figure 7.1**, as part of its work, with the intent to visualize as many treatment and reuse aspects as possible within a complete system. By creating this hypothetical yet comprehensive diagram, working group members hope that readers will more easily visualize various treatments or approaches and how they fit within the larger system of water flows and management, allowing readers to visualize their particular municipality's context and needs for potential implementation in a modular format.

Drivers Motivating Norman's Exploration of Hybrid Treatment and Reuse Systems

The City of Norman, a city of approximately 130,000 residents in central Oklahoma, is the state's third-largest city. The city utilizes three water sources: groundwater from the Central Oklahoma Aquifer, also known as the Garber-Wellington Aquifer, surface water from Lake Thunderbird (a multiple-use reservoir shared with the Cities of Del City and Midwest City), and treated municipal water from the City of Oklahoma City. Norman maintains more than 40,000 water service connections.

The City of Norman's Water Treatment Division operates and maintains the Vernon Campbell Water Treatment Plant through the Norman Utilities Authority (NUA). The plant is currently capable of treating 17 million gallons of water per day and features ozonation for taste and odor control, as well as ultraviolet light as the primary disinfection method. In addition, staff maintain 43 active water well sites, 26 inactive water well

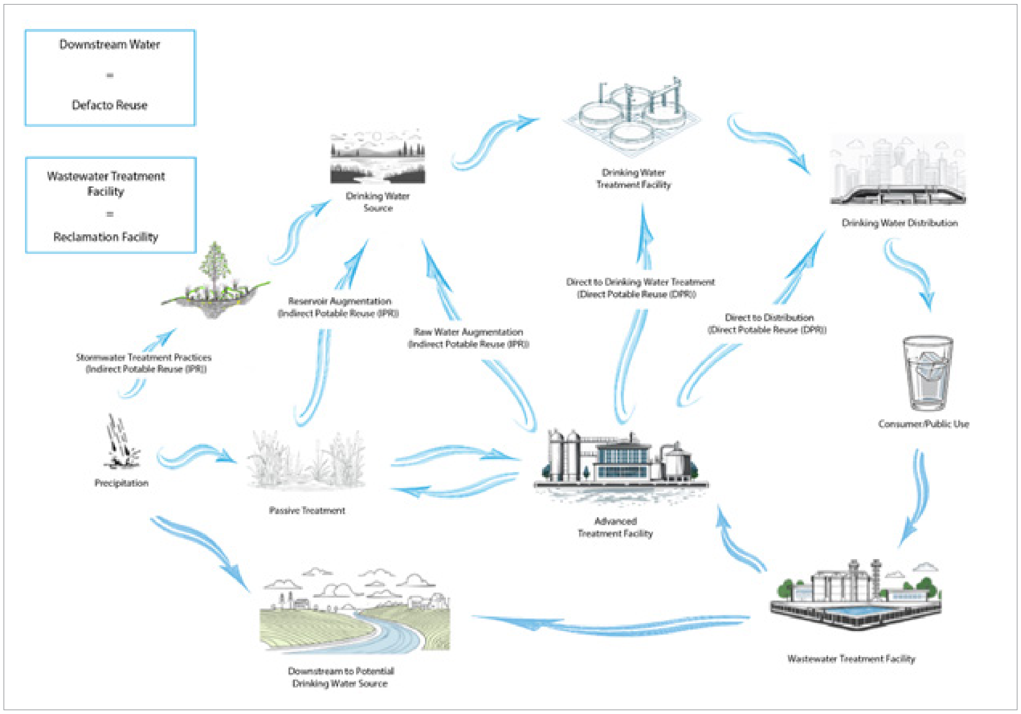

Figure 7.1. A hypothetical treatment and reuse diagram demonstrating potential pathways for treatment and reuse.

sites, and five water towers. In 2023, the division sent a total of 5.32 billion gallons of water to City of Norman water customers, including 3.40 billion gallons from the water treatment plant, 1.55 billion gallons from wells, and 367 million gallons from Oklahoma City.[4]

The City of Norman Water Reclamation Facility's mission is to produce highly treated reclaimed water at the lowest cost to customers with the ultimate vision to produce a quality water product that allows current and future generations to enjoy a high quality of life. The Norman Water Reclamation Facility (NWRF) is a Secondary Advanced Wastewater Treatment (AWT) facility consisting of complete mixed activated sludge as the primary treatment process and ultraviolet disinfection and odor control for secondary treatment. The NWRF is designed to treat an annual average of 17 million gallons per day (MGD) and up to 36 MGD during wet weather flows. Currently, the facility is treating an average monthly flow of 11 MGD.[5] In early 2020, the Norman IPR pilot project was initiated to explore different technologies and strategies to optimize reuse; the pilot project began due to a variety of factors and drivers spurring Norman to have strong interest in water reuse.

Specifically, Norman is an excellent candidate for a case study on a municipality's experience with water reuse and hybrid treatment techniques, given its underlying drivers and needs related to water supply management, its geography, and proximity to research expertise. NUA had several primary motivations to explore the potential for novel water treatment and reuse options: projections for increasing demand with a simultaneous goal to keep water use flat; nutrient management needs; and the potential for erratic or decreasing water supply due to recurring drought, increasing regulatory requirements limiting well use, and changes in surface water allotment values.

First, population growth projections[6] indicate that demands on the Norman water system may soon outpace water supply[1]. Simultaneously, NUA has expressed a desire to contribute towards meeting the statewide Water for 2060 goal, which seeks to use no more fresh water statewide in 2060 than the state did in 2010.[7] These demands

1 Figure 10-1, page 64; Figure 10-2, Table 10-2 page 65. https://assets.rdgusa.com/files/AIM%20Norman%20Water%20Master%20Plan%20APPROVED%20by%20SubCommittee%20on%2001.28.2025.pdf

and goals motivated NUA to consider water reuse opportunities to address the potential for gaps between anticipated supply and projected increasing needs.

NUA also recognized that potential tightening of regulatory restrictions on specific metals content in drinking water (particularly chromium and vanadium) may reduce the number of groundwater wells able to contribute to water needs, future surface water allotment values may decrease, and repeated or prolonged droughts may curtail available water supply.[2] Given this potential, NUA was motivated to augment its water supply as a hedge against these possible future conditions.

In addition, the primary water source for the City of Norman, Lake Thunderbird, is designated as a Sensitive Water Supply (SWS)[3] with limited capacity to handle water demand growth and has been deemed as an "impaired" (303d-listed) water body due to turbidity, chlorophyll-a (due to excess nutrients, primarily phosphorus) and low dissolved oxygen. As an impaired water body, the lake must be managed according to the *Final Lake Thunderbird Report for Nutrient, Turbidity, and Dissolved Oxygen TMDLs* (Total Maximum Daily Loads) to address issues with chlorophyll-a, turbidity, and low dissolved oxygen (2013).[9] Therefore, not only the management of overall water supply, but also the minimization of phosphorus in water reclamation facility water and the management of phosphorus and other nutrients from stormwater runoff, contribute significantly to the city's interest in exploring the potential for wetlands to contribute to additional reductions in nutrient loads.

As a result of the motivations above, over the past decade, the NUA has evaluated options to augment future water supply twice. First, the city established a strategic *2060 Water Supply Plan* in 2014, and through this planning process, NUA evaluated 15 water supply sources to augment supply. After evaluating each potential source, Lake Thunderbird Augmentation using IPR was identified as the top priority solution for the city's growing water needs in a resource-constrained environment, followed by utilizing new groundwater wells tapping the Garber-Wellington Aquifer, and purchasing additional water from Oklahoma City.[10]

The study was repeated in 2024 as part of the *AIM Norman Water Utility Master Plan*; in this study, eight alternatives for additional water supply were evaluated, with six of these the same as those evaluated in 2014 (NOTE: some sources evaluated in 2014 were not re-evaluated in 2024 due to being determined as non-viable). In the 2024 study, slightly different assumptions and priorities were taken into account; nevertheless, the same top 3 priority solutions were identified, in slightly different order, with water purchase from Oklahoma City ranking highest, utilizing new groundwater wells ranking second, and Lake Thunderbird Augmentation (IPR) ranking third.[11] The adjustments in rankings from the 2014 study to the 2024 study were closely linked to implementation challenges for IPR, including the time to implementation, upfront investment costs to generate returns on those investments, regulatory limitations, and the need for multi-municipality agreements.

Strategic Opportunities for the City of Norman

Understanding the various demands on the city to address water quantity and quality issues, the City of Norman has several strategic opportunities that lend themselves towards the potential for pursuing hybrid treatment and reuse approaches. First, the city has formed strong relationships with researchers that provide the city avenues to evaluate and test possible solutions. Specifically, given Norman's ongoing work to address

2 Ibid.

3 It is important to note that Lake Thunderbird is owned by the U.S. Bureau of Reclamation. Furthermore, the reservoir is a shared resource that provides the primary water supply for not only the City of Norman but also Midwest City and Del City. As such, Lake Thunderbird water supply is managed through the Central Oklahoma Master Conservancy District (https://www.comcd.net/).

challenges related to variable water quality and quantity conditions, in 2021, near the beginning of the S3OK project, researchers invited the City of Norman Utilities Director to collaborate with the research team, to advise the direction of the S3OK project from a municipal water management perspective, and to ensure that S3OK research aligned with practitioner priorities to address challenges related to water quantity and quality. Researchers from the University of Oklahoma, Oklahoma State University, and Southwestern Oklahoma State University have contributed technical approaches to this work.

The NUA had a history of working with OU researchers on several smaller collaborative projects, and these positive experiences created an environment of trust that prompted the City to be willing to join in an advisory capacity. In addition, the City had an interest in obtaining additional data on the efficacy of treatment wetlands under a variety of conditions within a wastewater treatment system[4] to explore how a natural infrastructure approach could contribute to a potential IPR system in Norman. Overall, the S3OK opportunity provided the ability to leverage federal funding to enhance data collection opportunities and offer proof of concept for one aspect of an IPR system at a mesocosm scale.

The City of Norman has also laid significant groundwork in its exploration of hybrid treatment and reuse approaches through synergistic opportunities, including a collaboration between S3OK researchers, the city, and the U.S. Bureau of Reclamation to research stormwater treatment wetlands and explore a scaled-up environment. The U.S. Bureau of Reclamation (USBR) also served on the S3OK OLAN as a project advisor.

Through this synergistic effort, USBR contributed both research time and funding, and further brought in expertise from the U.S. Geological Survey to look at Advanced Water Treatment (AWT) systems and the U.S. Environmental Protection Agency to examine groundwater issues. Following on from these collaborations, U.S. EPA scientists and USGS PFAS specialists also contributed research and expertise to the synergistic research outcomes. Individuals involved in these myriad synergistic projects have noted that the breadth and duration of these wide-ranging, multi-institutional collaborations have been highly unusual, yet extremely beneficial in tackling a wicked problem of this magnitude, and that the breadth of collaborators involved has moved results forward more quickly than if each individual project had occurred without the synergies across projects.

Proposed Solutions Advanced for the City of Norman

To explore how a natural infrastructure approach, treatment wetlands, could contribute to a potential IPR system in Norman, the City and S3OK researchers at OU's Center for Restoration of Ecosystems and Watersheds (CREW) agreed upon a physically appropriate demonstration site at the NWRF to begin this exploration at a small scale. Shortly thereafter, S3OK CREW researchers constructed experimental treatment wetland mesocosms (i.e., small-scale wetlands).

The mesocosm treatment wetland compound consists of 52 individual 220-L batch reactors, with 50 experimental units and two units reserved as vegetation nurseries. Half of the experimental mesocosms (25) receive secondarily treated municipal wastewater, prior to ultraviolet treatment. The other half (25) receives surface water from an urban stormwater-dominated stream. For each water source, the experimental design includes five open water control (OWC), ten free water surface (FWS), and ten subsurface flow (SSF) mesocosms. Half of each of the FWS and SSF treatment wetland mesocosms are planted with soft rush (*Juncus effusus*), while the remaining half remain unplanted. FWS and SSF are well-established treatment wetland designs, each emphasizing different water quality improvement processes. OWC experimental units serve as non-wetland controls.

4 Treatment wetlands would serve as tertiary polishing process units, and at this time their regulatory status (e.g., where the NPDES permit point is located) is still an unknown.

Although the role of treatment wetlands in addressing conventional wastewater and stormwater pollutants (e.g., solids, oxygen-demanding substances, nutrients) is well established, their ability to address emerging contaminants (e.g., typically non-regulated personal care products, pharmaceuticals, industrial and agricultural compounds) is an area of active exploration.

After an initialization period to establish vegetation plantings, develop properly flooded soil conditions, and create and adjust operational, maintenance and sampling protocols, four sets of experiments have been completed. Given the collaborative nature of this endeavor, future experiments are planned, using multiple sources of existing and proposed funding.

An initial experiment examined the critical role of hydraulic retention time (HRT) in treatment performance. Based on the treatment wetlands literature, three HRTs—three, seven, and 10 days—were examined. Changes in concentrations of conventional constituents (e.g., solids, nutrients) and carbamazepine were examined. Carbamazepine, an anti-seizure medication, served as a surrogate for emerging contaminants due to its environmental persistence, widespread distribution, and recalcitrance to traditional wastewater treatment processes[12]. Performance varied by hydraulic design (FWS and SSF), but

The experimental treatment wetland mesocosms were intended to evaluate the effectiveness of multiple naturally occurring biogeochemical, physical, microbiological, and ecological wetland processes to remove specific conventional and emerging water quality constituents, and thereby inform the conceptual design of a future pilot wetland (Figures 7.2 to 7.5).

Figure 7.2. Aerial image of the mesocosm tanks at the City of Norman Water Reclamation Facility

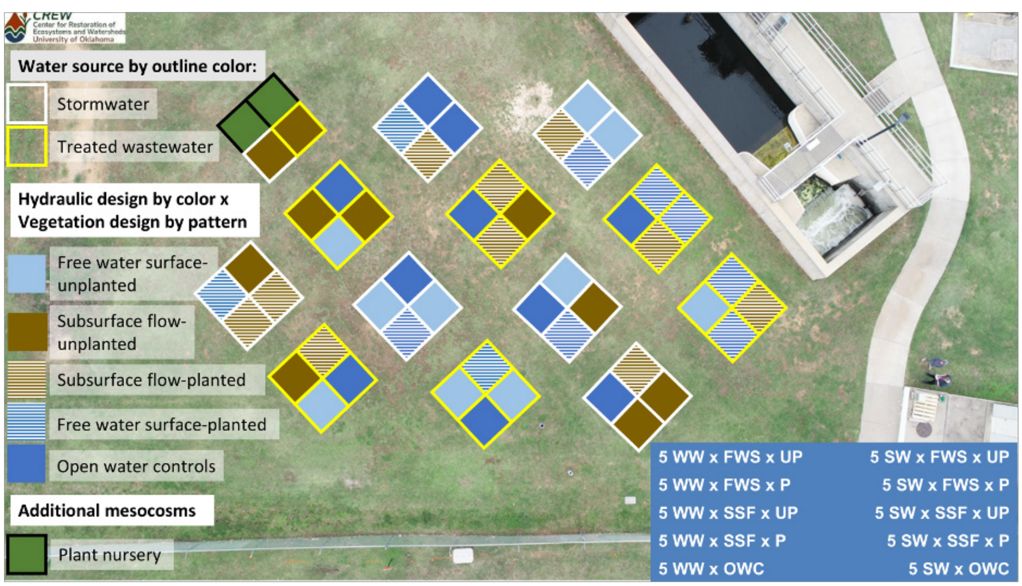

Figure 7.3. Mesocosm site layout by water type, hydraulic design, and vegetation scheme

not with the presence of vegetation. In the end, an HRT of seven days was determined to be an appropriate metric for future experiments.

A second experiment investigated the role of active aeration in promoting aerobic removal mechanisms. Small solar-powered aerators were deployed in a portion of the experimental mesocosms, and carbamazepine, sulfamethoxazole, and bisphenol-A served as emerging contaminant surrogates, due to environmental persistence, widespread distribution, and easy detection.[13, 14, 15] Conventional constituents were also monitored. Overall, removal efficiencies varied by constituent, hydraulic design, and vegetation scheme, but the role of active aeration was found to be negligible.

Figure 7.4. HOBO (brand) weather station in operation at the Norman Water Reclamation Facility mesocosm site.

Figure 7.5 University of Oklahoma Center for Restoration of Ecosystems and Watersheds (CREW) students planting the vegetated mesocosms

A third experiment explored the role of solar radiation, which drives the photolysis degradation pathway. Conducted in peak solar radiation in the middle of summer, half of the mesocosms were shaded, and the other half were left exposed. Conventional constituents, along with carbamazepine and sulfamethoxazole as emerging contaminant surrogates, were monitored. The role of solar radiation in contaminant concentration changes was found to be mixed.

The last completed experiment investigated the role of seasonality in removing both conventional and emerging contaminants from treated municipal wastewater and surface water dominated by urban runoff in treatment wetland mesocosms. Standard operational conditions were maintained in all mesocosms, and no experimental manipulations were made. In addition to the full suite of conventional constituents and in-house analyses of selected emerging contaminants, a suite of 86 additional emerging contaminants (pesticides, pharmaceuticals and personal care products, and per- and poly-fluorinated alkyl substances) were measured. Variability in source water concentrations was quite large, and removal performance subsequently varied. The role of both temperature and photoperiod on treatment wetland performance is important, and results will contribute to future designs.

The treatment wetland mesocosm work completed and planned was made possible by the dynamic and productive partnership between university researchers, City of Norman staff, and multiple other partners. Additional mesocosm experiments exploring the role of biological productivity, specific sorption mechanisms, and other research questions are planned. Perhaps most promising is planned work to model mesocosm results to produce pilot-scale treatment wetland designs.

Overall, a broad range of biogeochemical processes in treatment wetlands appears to have an effect on the aqueous concentrations of emerging contaminants. Based on the results to date, a combination of hydrologic designs, including open water, free water surface, and subsurface flow wetlands, would likely result in the greatest concentration changes of the greatest number of emerging contaminants. Repeated sequences of aerobic and anaerobic process units are necessary, similar to current design guidance for nitrogen removal in treatment wetlands. Given the hundreds of thousands of emerging contaminants in the environment, any specific pilot-scale or full-scale design must be based on well-defined objectives and specific constituents of interest.

Additional Solutions for Future Consideration

In addition to the work specific to the City of Norman case study, further technical work was undertaken through the S3OK project, which provides new avenues for both Norman and other Oklahoma municipalities to consider if they wish to explore water treatment and reuse technologies under specific technical, budgetary, and regulatory constraints. Key findings from these technical approaches are outlined below.

Municipal Wastewater

Additional solutions for future considerations involving municipal wastewater include:

- Enhanced biodegradation of CECs for municipal water quality
- Catalysts for advanced oxidation water purification
- Novel oxidation systems for municipal wastewater treatment and reuse
- Advanced oxidation processes for wastewater reuse

Enhanced Biodegradation of CECs for Municipal Water Quality

The Krzmarzick lab in the School of Civil and Environmental Engineering at Oklahoma State University conducted bench-top experiments using fill-and-draw reactors to simulate aerobic digestion processes at water recovery facilities. The reactors contained sludge from the aerobic digestors at a local Oklahoma wastewater treatment plant and were spiked with two CECs[5]—carbamazepine (a pharmaceutical) and imidacloprid (a neonicotinoid insecticide). Vitamin additions, redox cycling (seven days aerobic, seven days anaerobic), and longer solids retention times (30 days, instead of the base condition of 15 days) were tested as experimental manipulations, both alone and in combination with each other. Over a period of 30 days, the concentrations of carbamazepine and imidacloprid slowly decreased in the reactors, reaching approximately 80% of the initial input values, which were sustained for an additional 30 days. This result is encouraging in that it shows aerobic digesters are capable of CEC degradation; however, the degradation was too slow to completely remove the compounds.

Although vitamins were expected to enhance degradation (as they are often necessary cofactors for catabolic enzymes), as were longer solids retention times (to allow slower-growing bacteria to become established), these treatments did not have a measurable effect on the degradation rates. Alternating redox conditions slowed the degradation rates compared to the other conditions, limiting the degradation process. The alternating redox conditions suggest that anaerobic digesters, which are more often used in facilities (as opposed to aerobic digesters), may be less capable of

5 From Glassmeyer et al. 2017[25], "Initially termed "emerging contaminants," there is some misperception that the term suggests that these chemicals have only recently been released into the environment. In fact, these chemicals have been released as long as they have been in use, and some compounds (such as caffeine) have been detected in wastewater (Shuval and Gruener, 1973; Shackelford and Cline, 1986), surface water (Donaldson, 1977; Sheldon and Hites, 1978; Eganhouse et al., 1983; Richardson and Bowron, 1985), and drinking water (Coleman et al., 1980) for several decades. What is emerging is greater awareness by the general public of the presence of these contaminants in the environment and the direct link of environmental presence to household use. The ability of environmental scientists to detect extremely low ambient concentrations of these contaminants, aided by improvements to the analytical instrumentation, further fosters this awareness. Thus, the term "contaminants of emerging concern" (CECs) is a more appropriate choice when describing these contaminants in aggregate."

degrading carbamazepine and imidacloprid. Attempts to enrich for degrading communities are still underway; however, degradation stalls in the absence of digester sludge, suggesting a yet-to-be-uncovered cometabolic substrate or necessary cofactor in the sludge.

Furthermore, the research group investigated the microbial communities and the degradation capabilities of sediment in the FWS wetland mesocosms described above and in the receiving stream at the NWRF. The degradation of carbamazepine and imidacloprid was tested in bench-scale microcosms containing sediment. Over at least two months, no microbial degradation occurred of these two compounds in the absence of any other carbon source under aerobic conditions.

When both vitamins and a mixture of carbon sources were also added, degradation proceeded, albeit slowly. This shows that microbial degradation of these CECs are expected to be slow in natural-like systems.

Interestingly, although planted microcosms exhibited a higher relative abundance of several taxa associated with CEC degradation, no differences were observed in our experiments between the planted and unplanted mesocosms in these tests. The receiving stream also showed distinct bacterial communities between sediments near the outflow, sediments about 100-200 feet downstream, sediments beyond 200 feet downstream, and sediments upriver of the outflow in the Canadian River. However, these sediments all acted similarly in the experiments. This suggests that receiving water bodies, such as streams, will experience alterations in microbial communities due to the treated effluent; however, these alterations may not include an enrichment of CEC-degrading capabilities. Altogether, these results demonstrate the difficulty in achieving CEC degradation with microbial systems, both within wastewater treatment and in nature-based systems.

Catalysts for Advanced Oxidation Water Purification

Municipalities seeking new and cost-effective approaches to water purification of toxic dyes may wish to consider recent work conducted by the Hubin research group at Southwestern Oklahoma State University (SWOSU). The Hubin research group at SWOSU has produced a large number of metal-binding molecules (ligands) that have unique properties allowing them to strongly bind reactive, but non-toxic, metal ions like manganese and iron. These non-toxic metal ions are utilized in biological enzyme systems to activate oxygen (O2) and hydrogen peroxide (H2O2) for the oxidative transformation of one organic compound into another. Bound to Hubin's "cross-bridged macrocycle" ligands, these metals efficiently activate oxygen and hydrogen peroxide to destroy organic contaminants in water, as illustrated by the decolorization of potentially toxic textile dyes and antibiotics that may lead to antibiotic resistance **(Figure 7.6)**.

Previous work focused on proving that the catalysts were stable under the reaction conditions and were effective at removing or destroying the organic contaminants, with both outcomes being attained. However, for this

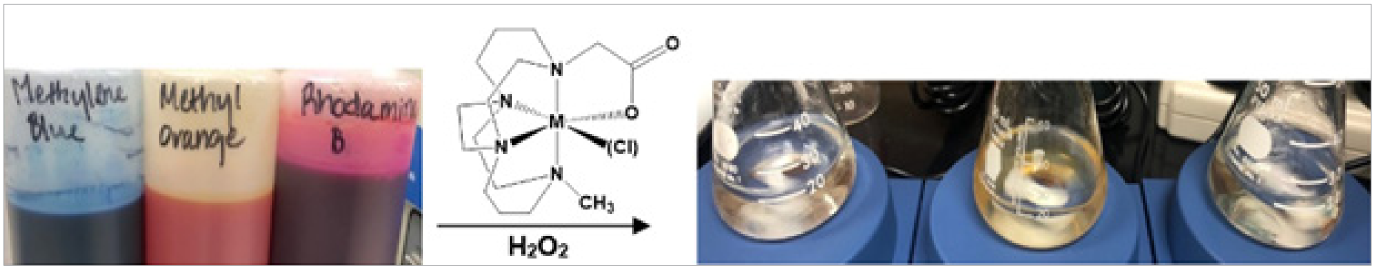

Figure 7.6. Common dye pollutants Methylene Blue, Methyl Orange, and Rhodamine B before (left) and after (right) catalytic oxidation by macrocyclic catalysts using hydrogen peroxide.

technology to become an effective part of a water purification system, either at the large scale in a water treatment plant, or in a small scale in a home water purifier, the catalysts will need to be produced in a recyclable solid form rather than as a soluble compound, which doesn't allow reuse and recycling. The current work is focused on binding the catalyst complexes to readily available water softener resins. In this form, the water to be purified simply needs to be stirred with or passed through the catalyst-containing resin in the presence of O2 or H2O2. The resin can be used to purify much more water this way. Through this work, the Hubin group has demonstrated that resin-fixed catalysts are recyclable with minimal loss of activity over multiple cycles of water purification.

This work would fit best with the "Advanced Treatment Facility" component of the water treatment and reuse diagram (see Figure 7.1) presented above. For this use, this technology would likely be a large-scale component of the facility with a cartridge filled with the catalyst-containing resin to treat a large quantity of water at a time before recharging the catalyst on the resin cartridge **(Figure 7.7)**. Potentially, the technology could also work on a small scale, for example, at an individual's home, much like a current water softener resin system works, or even as an add-on component of a typical water softener.

Novel Oxidation Systems for Municipal Wastewater Treatment and Reuse

The Mangalgiri lab in the Department of Biosystems and Agricultural Engineering at Oklahoma State University has been developing novel oxidation methods to enhance the treatment efficiencies of CECs in water reuse scenarios, which may serve as alternatives to conventional oxidation systems in water reuse and wastewater treatment. One such treatment is based on catalysts developed by the Hubin research group at SWOSU, as described above. Current work has tested the applications of select manganese and iron tetraaza macrocyclic catalysts for the degradation of antibiotics, a class of CEC that widely persists in wastewater effluents.

Preliminary work has focused on four antibiotic classes: fluoroquinolones, macrolides, sulfonamides, and tetracyclines. The tested antibiotic classes differ in terms of usage (which impact their prevalence in different wastewater types), structure and functional groups (which influence their physicochemical properties, such as acid base speciation, charge distribution, solubility, sorption onto solids) as well as bioavailability, toxicity, pharmacological mode of action. These are being tested in homogeneous and heterogeneous systems in laboratory-grade deionized water to determine fundamental degradation kinetics that will be used to design engineered systems for real-world applications.

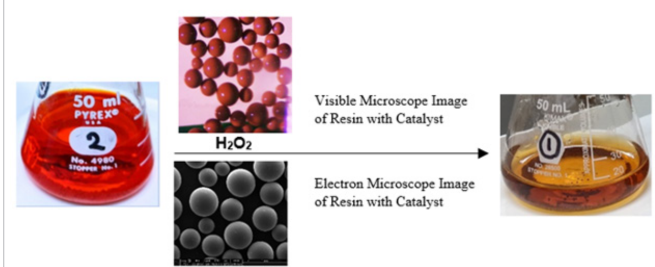

Figure 7.7. Methyl Orange dye in a reaction flask with solid state resin catalyst prior to oxidative destruction (left), optical and scanning electron microscope images of the resin catalyst (center), and significantly reduced coloration of the same dye after catalytic oxidation (right).

Preliminary work has shown degradation of up to 80% of tested antibiotics in bench-scale scenarios using lab-grade deionized water and real wastewater. It is important to note that, for the purposes of preliminary testing, wastewater was collected from animal lagoons, which is of lower quality than municipal wastewater. Future work will focus on testing the efficiency of catalysts developed by the Hubin lab in a flow-through system and the development of a demonstration unit for at-home, small-scale, and large-scale treatment.

Advanced Oxidation Processes for Wastewater Reuse

The Mangalgiri lab determined the applicability of existing advanced oxidation processes (AOPs) to address water quality concerns of relevance to rural and urban water reuse scenarios. While AOPs including UV- and ozone-based treatment are already used in municipal wastewater reuse, the treatment efficiency of these systems in degrading CECs is highly dependent on the composition of the water. Preliminary laboratory work assessed the behavior of standard AOPs (where oxidants such as hydrogen peroxide, persulfate, and free chlorine are paired with UV irradiation) in non-standard wastewaters such as produced water, lagoon water, and rural wastewater, and compared the scavenging behavior of wastewater streams to municipal wastewater effluent as a way to establish the applicability of these systems in alternate water reuse scenarios.

This work will result in a database of oxidant scavenging properties that will contribute to the development of mathematical models to predict real-life behavior of wastewater streams, thereby better informing pilot-scale studies for full-scale implementation of water reuse. Future work in this lab will also include ozone-based treatment options, which are relevant to Oklahoma.

Innovative Stormwater Treatment

The Oklahoma Water Survey at the University of Oklahoma, under the direction of Dr. Jason Vogel, has utilized S3OK funding to continue research on the use of industrial byproducts as a bioretention cell media amendment for targeted removal of neonicotinoid insecticides (under the "Innovative Stormwater Treatment" in the Treatment and Reuse Diagram (see Figure 7.1). This research builds on over a decade of research by the Vogel research team that has demonstrated that using fly ash as a bioretention amendment media can improve the removal efficiency of phosphorus, metals, and fecal indicator bacteria by bioretention cells.[16, 17, 18]

Bioretention cells are landscaped depressions that capture, filter, and infiltrate stormwater to improve water quality. If the native soil does not adequately infiltrate enough water to capture the "stormwater volume," which is often considered the runoff from impervious surfaces for the 85th or 90th percentile storm, bioretention media is brought in to filter pollutants from the media. By adding a small percentage (i.e., 5%) of an industrial byproduct (such as fly ash) into the typical sieved sand media, water quality improvement can be enhanced. The mass removal efficiency of both traditional (i.e., nutrients, metals) and emerging contaminants (i.e., neonicotinoids, polycyclic aromatic hydrocarbons) through the use of orifice outlets combined with amendments in bioretention underdrains was studied as a potential maintenance improvement for utilizing media amendments. Laboratory studies indicated that steel slag, aggregated small particles of fly ash, and biochar all had the potential for removing neonicotinoids from stormwater runoff.

Preliminary results of field studies conducted on replicated bioretention cells at a parking lot owned by the Grand River Dam Authority (GRDA) in Langley, Oklahoma, indicate that not using an orifice on the underdrain is most effective in allowing for the maximum amount of water to be filtered as possible. Preliminary results also indicate that all three byproducts (steel slag, biochar, and aggregated fly ash) show promise for helping remove dissolved insecticides from bioretention underdrain water. However, the bioretention cell media was also very effective at removing the insecticides, so the mass removal in the underdrain was usually less than what was removed in the actual bioretention cell media, because only a fraction of the influent insecticide remained once it reached the underdrain. For the Norman example shown above, these results could be utilized to improve the quality of stormwater entering the treatment wetlands or be utilized independently from the reuse scenario to improve the quality of stormwater runoff in urban settings.

Measurement of Surrogate CEC Test Compounds for Wastewater Reuse Systems

The Mangalgiri lab in the Department of Biosystems and Agricultural Engineering at OSU worked to identify a suite of CECs that can serve as surrogate test compounds to determine the efficiency of upcoming and existing oxidation systems. This work led to the identification of the gabapentin class of pharmaceuticals as a test compound that should be tested along with currently identified compounds. The gabapentin class of pharmaceuticals is small enough to bypass the reverse osmosis membrane at low but measurable concentrations and thus must be treated using post-membrane oxidation methods. Currently used compounds include caffeine, atenolol, DEET, 1,4-dioxane, acetone, and gemfibrozil. The identification of gabapentin and other gabapentinoids adds to the variety of compound chemistries currently being tested.

The lab has developed kinetic models to predict the degradation of gabapentin in standard advanced oxidation systems currently used in potable water reuse. Future work in this area will include the identification of degradation byproducts of gabapentin and the establishment of downstream toxicity.

Technical and Regulatory Challenges and Other Considerations of Importance

Despite the robust partnerships that enhanced the City of Norman's ability to make progress in evaluating and testing solutions, several key challenges and considerations must be acknowledged. Many of these are not specific to a Norman context and would need to be addressed regardless of project location.

Public Support and Willingness to Pay for Municipal Wastewater Reuse Programs

Municipal wastewater reuse is a crucial strategy for addressing water scarcity, particularly in regions where climate variability and population growth put a strain on water resources. However, regardless of the soundness of any particular technical approach or combination of approaches, water reuse will never be a realistic solution if the public does not support its implementation. Public concerns regarding the safety of reused water and support for new fees or taxes to cover the added infrastructure, as well as related operation and maintenance costs, must be addressed for reuse to move forward in any given community. For non-potable reuse, dual piping is needed, requiring the installation of purple pipe (used to signify reclaimed water for non-potable reuse). For potable reuse, the costs associated with the construction and operation of advanced treatment facilities can be a significant barrier for many communities.

To better understand Oklahomans' support for water reuse technologies and programs, S3OK researchers used a custom-designed panel survey of over 2,600 Oklahomans, called the Mesoscale Integrated Socio-geographic Network (M-SISNet). They developed a set of questions that were asked on the survey to assess public support and willingness to pay for municipal wastewater reuse **(Figure 7.8)**.[19]

The survey measured public support for a statewide program that would offer financial assistance, such as infrastructure grants and low-interest loans, to cities, towns, and municipalities implementing municipal wastewater reuse projects. It also assessed support for local initiatives by asking respondents whether they would want their city or town to apply for resources to build a wastewater reuse system. In addition to measures of state and local program support, the survey also captured respondents' willingness to pay for state programs by providing respondents with hypothetical, randomized costs that would be implemented over ten years.

The study found that the public was supportive of municipal wastewater reuse at the state level (74% of respondents) and willing to pay up to $30 per month for its implementation (see Figure 7.8). The implementation of a local program received slightly lower support (63% of respondents).

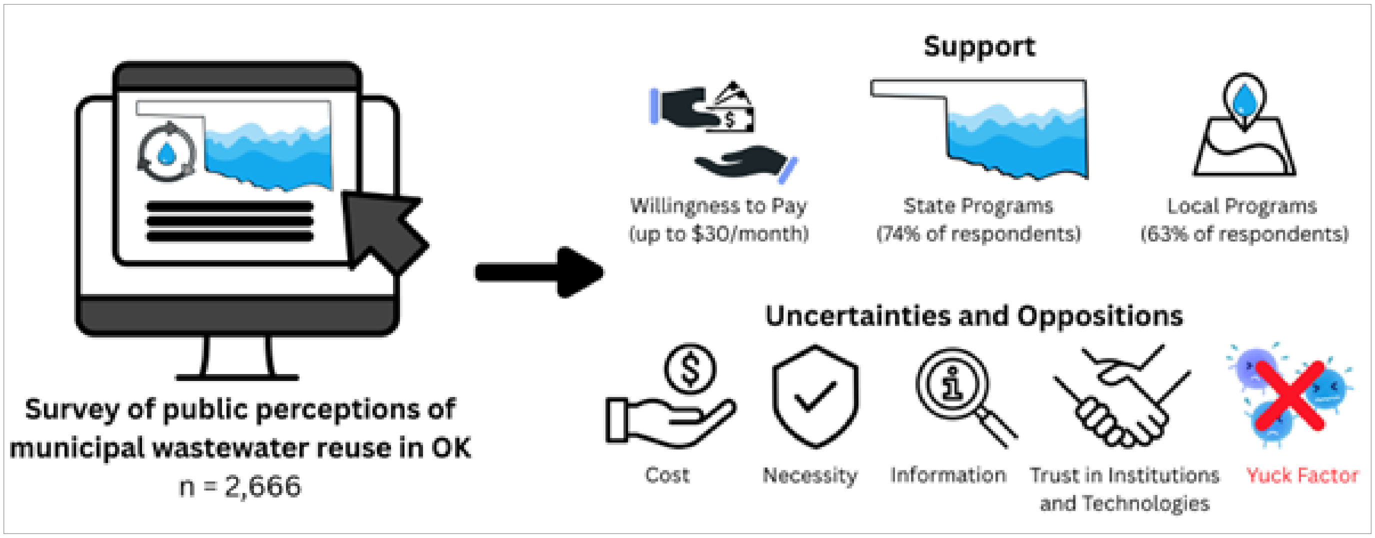

Figure 7.8. Diodosio et al. 2025 showed varying degrees of support for wastewater reuse options.

Meanwhile, several factors contributing to uncertainty and opposition emerged, including concerns over program cost, necessity, information, trust in institutions and technology, and the yuck factor – where the latter was a relatively minor concern among the public (see **Figure 7.8**).

Overall, 74% of respondents supported the statewide program if it could be implemented with existing resources, and 63% said they would want their city or town to seek resources to build a reuse system if the program were implemented. Despite significant differences in water resources, support remained fairly consistent across geographic regions. Approval for the statewide program was highest in the Upper Arkansas OCWP Watershed Planning Region, where 79% of respondents were in favor, and lowest in the Lower Arkansas region, where 62% expressed support. **Figure 7.9** shows public support (i.e., a vote in favor) for a statewide program that would offer financial assistance to cities, towns, and municipalities implementing municipal wastewater reuse projects by OCWP Watershed Planning Regions.

For the local program, support was strongest in the Southwest region, where 69% of respondents wanted their city or town to apply for resources, and lowest in the Eufaula region, where 51% expressed support. Support was also relatively consistent among respondents from urban, suburban, and rural areas. Suburban residents showed the highest support for the statewide program (77%), followed by urban residents (75%), while support was slightly lower among rural residents (73%). Differences were slightly more pronounced across socio-economic groups. For example, support was highest among respondents with more than a college degree (81%), followed by those with a college degree (76%), and lowest among those with less than a college degree (65%).

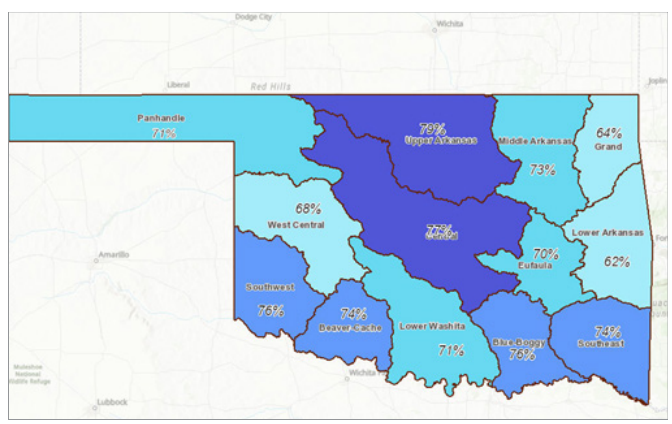

Figure 7.9. Map of percentage of public support (i.e., a vote in favor) for a statewide program that would offer financial assistance to cities, towns, and municipalities implementing municipal wastewater reuse projects, by OCWP Watershed Planning Regions.

Trust and initial perceptions of reuse played a greater role in shaping public support for the reuse programs than geographic or socio-economic factors. Beginning with trust, respondents were asked about their level of confidence in scientists who study water systems, the technology used in water systems, and the public officials and employees who manage them. Among those who reported high or complete trust in all three, 87% supported the statewide reuse program, and 73% supported the local initiative. In contrast, among those with little or no trust in all three, support dropped to 44% for the statewide program and 37% for the local initiative. A similar pattern emerged with respondents' initial impressions of reuse. Among those who had very negative first impressions of reuse, before seeing an explanation, only 47% supported the statewide program, and 31% supported the local initiative. Conversely, among those with very positive initial impressions, support was significantly higher, with 90% backing the statewide program and 89% favoring the local initiative.

In addition to trust and initial perceptions, cost was a significant factor in shaping public support for the statewide reuse program. Respondents who initially supported the program in the general question received a follow-up asking whether they would still vote for the program if it required them to pay [X] dollars per month for the next 120 months (10 years). [X] was a randomly assigned value ranging from $1 to $30, meaning some respondents saw a relatively low cost while others encountered a higher cost. This variation enabled the research team to estimate the price point at which respondents shifted from being willing to pay for the program to being unwilling to pay. In this case, that threshold fell between $4 and $5 per month for a 10 year period in the most basic set of models.

This type of analysis, known as contingent valuation, is widely used by economists to assess a population's willingness to pay for environmental policies and infrastructure programs, such as water reuse initiatives.[20, 21] By testing different price points, contingent valuation helps identify the financial limits of public support and provides policymakers with valuable insights when assessing the benefits and costs of new programs. However, it is important to note that there are multiple methods for estimating willingness to pay, each requiring different assumptions, models, and robustness tests. While the threshold of $4-$5 per month offers a preliminary estimate, more extensive analysis is underway to refine this range and provide a more comprehensive assessment.

The analysis above contributes to ongoing discussions about water reuse programs in Oklahoma by providing a data-driven understanding of public support, particularly the key factors influencing acceptance, namely, trust and initial impressions. It also offers valuable insights into public willingness to pay, which is essential for conducting benefit-cost analyses and informing policy decisions.

Readers who wish to explore these and other data further are encouraged to visit the S3OK Public Survey Dashboard,[6] which provides interactive access to all the survey data collected as part of the S3OK project.

It is also worth noting that the Oklahoma Water Reuse Action Plan (OWRAP), developed through a multi-agency collaborative effort in conjunction with the 2025 update to the Oklahoma Comprehensive Water Plan (OCWP), addresses multiple elements related to public acceptance, including:

- Developing information that illustrates the economic benefits of providing water suitable for the intended purpose.
- Organizing an Interagency Water Reuse Education and Outreach Team.
- Compiling existing education materials from across the nation and adapting them for use in Oklahoma.
- Evaluating and tracking how the perception of reuse is changing over time (statewide and/or targeted communities).

6 https://crcm.shinyapps.io/s3ok/

Regulatory Considerations

The regulatory status of the waterbody receiving reuse water can be a major challenge that must be considered when evaluating reuse opportunities. The presence of TMDLs, endangered species recovery plans, downstream water rights, and other special designations can pose significant challenges to cities pursuing reuse options, due to restrictions on new discharges and in-stream flow requirements for downstream users. This was the case for the City of Norman Case Study. In the City of Norman, because of its primary water source, Lake Thunderbird, being designated as both impaired (303d) and a Sensitive Water Supply (SWS), any point source discharge is currently disallowed until the Lake has been redesignated as an SWS-R (Sensitive Water Supply—Reuse). The state regulatory framework for doing so exists; however, the process of application, implementation, and evaluation has not yet been attempted.

Additionally, the regulatory environment surrounding the measurement and treatment of various contaminants and compounds is continually evolving. As of summer 2024, U.S. EPA National Primary Drinking Water Regulations (NPDWR) set maximum contaminant levels (MCLs) for six PFAS compounds, including contaminant mixtures, required of all public water systems to monitor these compounds by 2027, and remove them to federal standards by 2029 and report violations **(Table 7.1)**.[22] Municipalities planning upgrades to either mechanical or natural infrastructure-based water treatment or reuse systems will need to ensure that the project designs meet these standards.

Thousands of other contaminants are currently unregulated, but are of emerging concern to regulators, water system operators, and the public, especially as the regulatory environment surrounding these contaminants continues to evolve. CECs are enumerated by the U.S. EPA through the Drinking Water Contaminant Candidate List (CCL), which is updated every five years and contains a list of unregulated contaminants known to or anticipated to exist in drinking water supplies. The list is generated using best practice in research and nominations, and every five years the U.S. EPA takes action on at least five contaminants, deciding whether to regulate each of these.[23] CECs with known relevance for Oklahoma regulators include limited PFAS, manganese, lithium, personal care products such as medications, and microcystins (which cause harmful algal blooms).[25] While the City of Norman case study began to explore how treatment wetlands can be used as part of a hybrid treatment system to remove or decrease CECs in wastewater, and promising results were shown in this mesocosm phase, further research is needed.

Table 7.1 Six EPA-Regulated PFAS Compounds

Compound	Final MCLG	Final MCL (enforceable levels)
PFOA	Zero	4.0 parts per trillion (ppt) (also expressed as ng/L)
PFOS	Zero	4.0 ppt
PFHxS	10 ppt	10 ppt
PFNA	10 ppt	10 ppt
HFPO-DA (commonly known as GenX Chemicals)	10 ppt	10 ppt
Mixtures containing two or more of PFHxS, PFNA, HFPO-DA, and PFBS	1 (unitless) Hazard Index	1 (unitless) Hazard Index

Courtesy of the US EPA ("Per- and Polyfluoroalkyl Substances [PFAS] | US EPA" 2021)

Finally, the Oklahoma Water Reuse Action Plan (OWRAP) addresses many of the regulatory challenges. The OWRAP Regulatory Strategy Area focuses on treatment and water quality requirements, water rights, and potential downstream impacts associated with increased water reuse. Completed actions include regulations for non-potable reuse (ODEQ 656 and 627), IPR (ODEQ 628), and initial interorganizational meetings regarding direct potable reuse (DPR) regulations.

Key regulatory drivers or challenges identified include the protection of downstream water rights, the need for clarity on water rights "credits" for augmenting supplies through reuse projects and/or potential future water quality trading credits, and compliance with permit requirements for the quality and quantity of recycled water. To address these, the OWRAP proposes to:

- Prepare a concise guidance document or fact sheet summarizing the current legal ability to reuse municipal return flows and receive credit for augmenting supplies with recycled water.
- Evaluate what-if scenarios to assess the water availability implications of additional reuse using the updated Oklahoma H2O Tool.[7]

Sustainability

The Foltz Research Group,[8] under the direction of Dr. Mary Foltz in the Department of Civil and Environmental Engineering at Oklahoma State University, has been exploring the sustainability of treatment wetlands in collaboration with Dr. Diana Byrne at the University of Kentucky. Life cycle assessment (LCA), as defined by ISO standards 14040 and 14044, follows four steps: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation as described in **Figure 7.10**. LCA can be applied in many contexts to quantify environmental impacts associated with a product, system, or technology. Specifically, it can be applied to any of the areas depicted within Figure 7.10. Here, an LCA was applied to the City of Norman wetland mesocosms to quantify and compare life cycle environmental impacts associated with the different system designs.

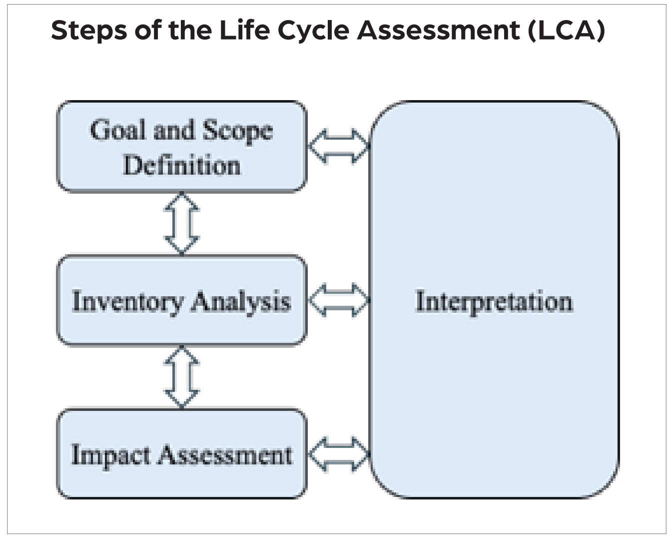

Figure 7.10. Steps of life cycle assessment.

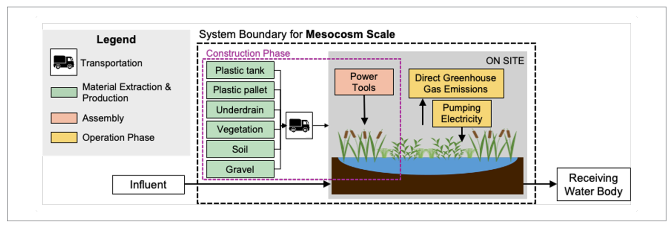

Figure 7.11. System Boundary for Mesocosm Scale.

The first step of LCA, goal and scope definition, included setting the system boundary, as shown in **Figure 7.11**. The material extraction and production, transportation of materials to the site, assembly of the wetland mesocosms, and operation of the mesocosms were considered. In the second step of LCA, inventory analysis, all inputs and outputs of the system based on the system boundary were considered. This included all materials necessary to build the mesocosms, as well as equipment for construction and operation, and emissions associated with the construction and operation of the mesocosms. Most of these inputs were obtained based on specific site construction details, and the emissions were gathered from the Ecoinvent database or published literature. In the third step of LCA, impact assessment, the TRACI 2.0 software was applied to translate emissions into

7 https://ok.hawqs.tamu.edu/#/
8 https://www.maryfoltz.org/

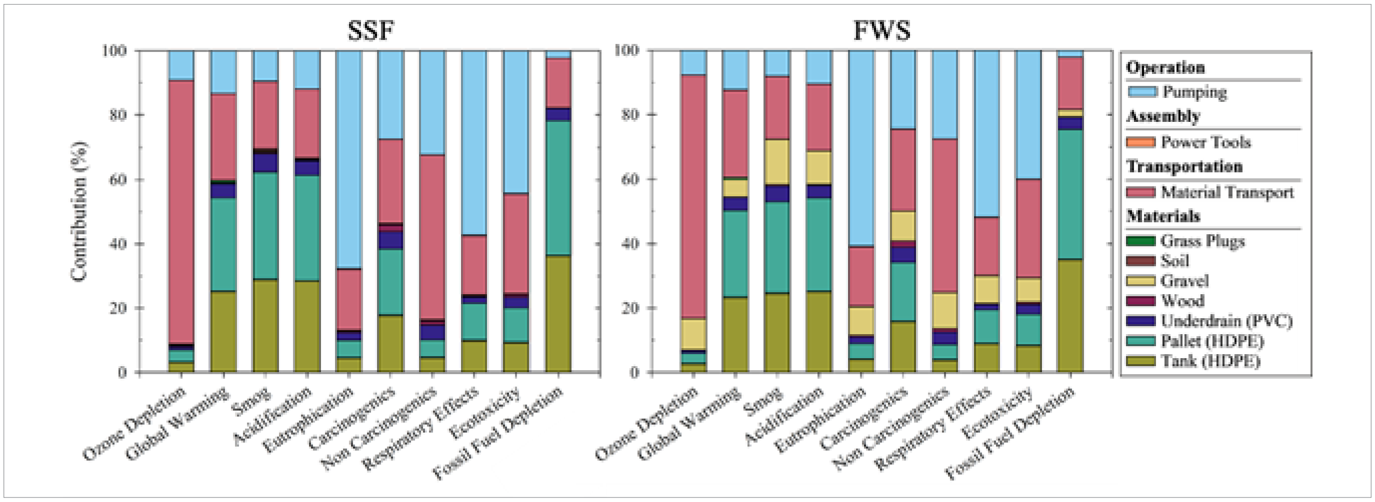

Figure 7.12. LCA results by inventory item for the subsurface flow (SSF) and free water surface (FWS) wetland mesocosms. Values reflect median results from uncertainty analysis, normalized to percent contribution for each impact category.

environmental impacts in categories such as global warming, eutrophication, and ozone depletion. Finally, the outcomes of the study were interpreted after running uncertainty analyses, which is the final step of LCA.

Generally, the hydrologic design (free water surface vs. subsurface flow) had a relatively minor impact on the resulting environmental impacts. Instead, the material production and transportation dominated emissions for all designs **(Figure 7.12)**. When scaling up these systems to full-scale operation, some materials will be unnecessary (e.g., plastic tanks), while other processes will become more important (e.g., excavation). Therefore, this approach should be replicated at the full scale to understand the impacts under that scenario.

While the construction and operation of wetlands can contribute to some environmental impacts, direct emissions from the water or soil surface are highly uncertain **(Figure 7.13)**. Direct emissions were estimated based on reports from the literature, and the variability in emissions between studies was notable. Environmental conditions, experimental considerations in measurement methods, and system design can all influence resulting emissions from wetlands. Therefore, it is important to consider factors that are within control for the given site when determining appropriate designs that minimize environmental contributions of the project over its lifetime.

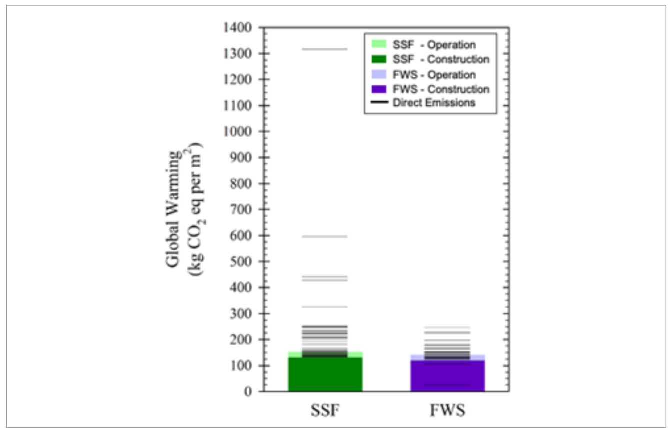

Figure 7.13. Lifetime global warming impact results for the subsurface flow (SSF) and free water surface (FWS) wetland mesocosms. Black bars represent direct emission data, collected from a literature review and converted to CO2 equivalent over a lifetime of 20 years, added to the global warming results from the construction and operation phases of the LCA (see Figure 7.12 for complete LCA results).

Plans for Future Technical Work

Given the initial success of collaborations between the City of Norman, S3OK researchers, and the Bureau of Reclamation, the team plans to take future steps to expand the exploration of integrating treatment wetlands as part of a water reuse program. If successful, the City of Norman Constructed Wetlands Project could provide important design criteria for full-scale treatment wetlands and yield essential data on how to build and integrate an engineered wetland into any utility's stormwater and/or wastewater treatment systems.

Although numerous larger scale projects have demonstrated success with treatment wetlands for wastewater treatment,[9] the S3OK work is a localized example of how treatment wetlands may be able to be utilized in a scenario with TMDL and within the specific Oklahoma regulatory context, adding significantly to the broader body of knowledge demonstrating that wetlands can be an effective augmentation to an existing water treatment system. Furthermore, knowledge gained from this work can be combined with other recently completed local pilot projects that have tested advanced active treatment technologies for further CEC and PFAS removal, thereby expanding the understanding of how hybrid treatment systems for indirect potable water reuse can be a viable strategy to increase our nation's usable water supplies.

Similarly, the public perception work conducted through the S3OK project provides important, new, publicly available resources for water managers to understand their residents' views on issues surrounding water availability and quality at a localized level.

Additionally, future technical work may provide insights into other components within the water treatment and reuse ecosystem that were outside the scope of the S3OK project's research. A brief overview of planned directions for future research is provided below.

Catalysts

Along with OSU assistant professor Kiranmayi Mangalgiri, an environmental engineer and water treatment specialist, the Hubin lab at SWOSU intends to scale up the production of the water purification catalyst-fixed resin and study several technical questions that need to be answered before potentially marketing this technology for large-scale water treatment plants or home-scale water purification.

Fortunately, the resins planned to be implemented are already available and used in bulk for water softening purposes. This catalyst-fixed resin approach would be similar to how a water softener works (See Figure 7.2). The resin is expected to remove organic contaminants for multiple cycles until the catalyst is no longer efficient. At that point, the resin can be "regenerated" by the addition of a fresh catalyst, which will bind the resin, producing a newly activated recycled resin. For example, water softeners have a regeneration cycle in which calcium and magnesium ("hard water" ions) are removed from the resin through a NaCl or KCl regeneration process. The water softening resin is then ready for reuse and can be used hundreds of times before needing to be replaced.

Future research will evaluate the feasibility of using a catalyst-fixed resin for organic contaminant removal, with periodic regeneration with fresh catalyst that allows long-term recycling of the same resin "cartridge" for many reuses **(Figure 7.14)**. Future work in this area will involve a comprehensive understanding of the impact that wastewater composition has on catalytic treatment, using synthetic wastewater of known composition.

Co-Treatment of Wastewater and Stormwater

From the ecological perspective of a functioning treatment wetland, which provides both water quality improvement benefits and other ecosystem services, the hydroperiod — essentially, the hydrologic signature of the wetland — is crucially important. Properly functioning wetlands need the right amount of water at the right time of year. One challenge in a region where annual evapotranspiration greatly exceeds precipitation is maintaining an appropriate hydroperiod,

9 Numerous examples of constructed wetlands used for wastewater treatment can be found in a U.S. EPA Case Study publication (https://www.epa.gov/sites/default/files/2018-07/documents/constructed_wetlands_for_wastewater_treatment_and_wildife_habitat_17_case_studies_epa832-r-93-005.pdf); and additional example includes the East Fork Water Reuse Project (https://www.ntmwd.com/171/East-Fork-Water-Reuse-Project).

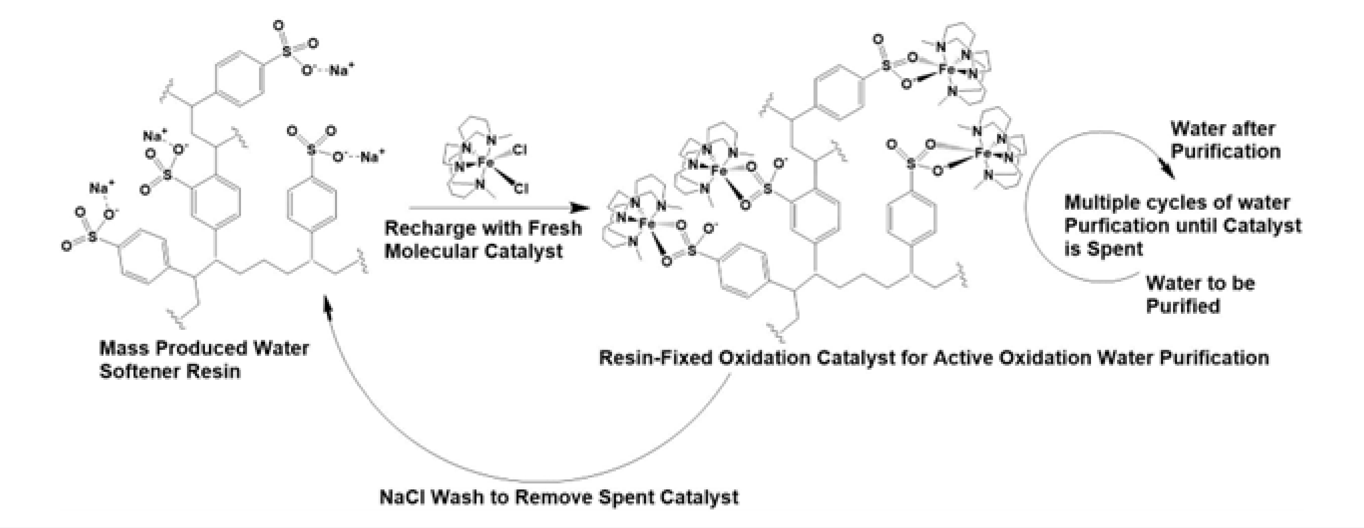

Figure 7.14. Proposed scheme for resin-based solid-state water purification by catalytic oxidation. The resin can be recharged by adding additional catalytic metal complex when it starts to be less effective (arrow at bottom). Likewise, the resin can treat a continuous flow of contaminated water (arrow at right) before needing recharging when performance is reduced.

especially in stormwater treatment wetlands, for which storm runoff events drive the hydrology.

One promising approach, which may be initially explored in the existing treatment wetland mesocosm compound, is co-treating municipal wastewater and stormwater. Municipal wastewater is produced at similar volumetric flow rates year-round and would provide adequate water to maintain wetland function. Coupled with consistent metering of municipal wastewater, a stormwater holding pond feeding a common wetland could potentially provide a promising option for improving the consistent and effective water quality of both sources of water, thereby supporting water reuse. The treatment wetland mesocosm compound provides a ready opportunity to explore this option.

Cost-Benefit Analysis of Water Treatment and Reuse Approaches

A cost-benefit analysis is needed to compare active, passive, and hybrid treatment options described earlier in this chapter. This analysis should encompass not only design and construction costs, but also long-term operation and maintenance costs. This cost-benefit analysis, combined with the public's willingness to pay for wastewater reuse as described above, will provide communities with valuable information for assessing the best options for their specific needs.

Concluding Guidance

It is important to note that the City of Norman began with a unique water profile, characterized by a very high-quality, secondarily treated effluent, a need for additional water supply to meet growing demands, and a regulatory need to reduce nutrient loading from stormwater. The research team acknowledges that these results may apply differently to different qualities of effluent and that further work is needed to understand the parameters under which these techniques would remain effective.

Overall, the S3OK research has demonstrated that Oklahoma-based research, informed by local stakeholders, can contribute to solutions of water supply resilience through water reuse options. We encourage Oklahoma practitioners to continue seeking creative solutions that utilize all available tools –including passive, hybrid, and advanced conventional treatment technologies – to implement practical water reuse and treatment that augment their local drinking water supply. Using our Treatment and Reuse Diagram as a framework, some specific recommendations based on recently completed S3OK include:

- **Innovative Stormwater Treatment**:
  - Implement innovative stormwater Best Management Practices (BMPs), such as bioretention cells, to improve the water quality of stormwater that may drain directly into surface waters or augment passive treatment wetlands for IPR.
- **Passive Treatment of Wastewater Effluent**:
  - The role of treatment wetlands in addressing conventional wastewater and stormwater pollutants (e.g., solids, oxygen-demanding substances, nutrients) is well established.
  - Thus, the work of the S3OK team addressed the ability of nature-based systems (treatment wetlands) to address emerging contaminants.
  - S3OK findings to date suggest that a hydraulic retention time of 7 days is worthy of further evaluation. Our findings also show that the employment of active aeration in treatment wetlands had a negligible effect on emerging contaminants. Furthermore, the roles of seasonality, temperature, and photoperiod on treatment wetland performance were found to be important. These new insights into treatment wetland performance will aid in the future development of design guidance.
- **Improved Advanced Wastewater Treatment Options**:
  - If catalysts are to be used to enhance "advanced oxidation" water treatment, the development of heterogeneous versions that can be reclaimed and recycled will be required.
  - Already accepted oxidation sources (H2O2, chlorine) for use with novel advanced oxidation processes will be required, as novel oxidants will increase cost, safety issues, and complexity of adding the new process.
  - Cost is a crucial factor in adding additional advanced oxidation treatment steps. Readily available materials (such as commercial water softener resins) must be leveraged in order to keep costs down. Small amounts of catalysts (if used) are required, and the materials must be recyclable and reusable for large quantities of water.
- **Public Education, Communication, and Involvement**:
  - Continue to integrate S3OK researchers and findings with the Oklahoma Water Reuse Action Plan and planning teams.
  - Continue the availability of public datasets and dashboards that allow stakeholders to analyze public perceptions data around water treatment and reuse.
- **Co-production of Oklahoma Policies for IPR/DPR**
  - S3OK demonstrated the importance of researchers, regulatory agencies, and cities/municipalities working together to address key challenges related to reuse implementation.
  - Implementing reuse is complex and requires multiple areas of expertise to address site-specific requirements, including public perceptions, costs, public willingness to pay, regulations, and the status of receiving waters (TMDLs, downstream water rights, etc.).
  - Based on this, the S3OK team fully supports the proposed creation of a top-level Inter-organizational Reuse Team composed of persons within supporting agencies and organizations with the expertise and capacity to advance water reuse in Oklahoma.

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