

Oklahoma's Wicked Problems:

A Framework for Socially
Sustainable Solutions
for Water, Land Use, &
Infrastructure



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5	CHAPTER 1 Introduction to Oklahoma's Wicked Problems
17	CHAPTER 2 Research Teams: Key Wicked Problem Focus Areas in Oklahoma
29	CHAPTER 3 S3OK Project Objectives, Goals, and Methodology
43	CHAPTER 4 Project Engagement, Structure, and Process
63	CHAPTER 5 Social and Scientific Challenges
74	CHAPTER 6 Subseasonal to Seasonal Weather Patterns
91	CHAPTER 7 Exploration of Hybrid Treatment and Reuse Alternatives for Wastewater and Stormwater in a Municipal Context: An Oklahoma Case Study and Resource Guide
119	CHAPTER 8 Solutions: Enhancing Water Availability for Agricultural and Oilfield Applications
144	CHAPTER 9 Nature of the Problems: How Subseasonal to Seasonal Weather Drives Wicked Problems for Natural Hazards and Utility Resilience



CHAPTER 1

Introduction to Oklahoma's Wicked Problems



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8	What is a Wicked Problem?
8	Toward Sustainable Solutions
9	Oklahoma's Unique Context
10	Socially Sustainable Solutions for Water, Land Use, and Infrastructure (S3OK)
11	The S3OK Project Overview
12	Integrated and Interdisciplinary Approach
13	Engagement
14	Framework for Addressing Wicked Problems: A Narrative Overview
16	References

CHAPTER 1

Introduction to Oklahoma's Wicked Problems

Like many states across the U.S., Oklahoma is confronting a set of complex, interrelated challenges involving weather variability, water quality and availability, land use transitions, and infrastructure resilience. Over the past five years, researchers and practitioners from across the state have engaged in a collaborative effort to better understand and address these challenges. This introductory chapter defines the concept of “wicked problems,” and introduces the S3OK project—an interdisciplinary initiative aimed at developing *socially sustainable solutions* for water, land use, and infrastructure systems in Oklahoma.

What is a Wicked Problem?

Complex issues that defy straightforward solutions, sometimes known as “wicked problems,” are emerging with increasing frequency and intensity. According to Webber, Lack, and Steel¹, wicked problems are complex social or cultural issues that are difficult or impossible to solve due to their interconnected and multifaceted nature, lack of clear solutions, and real-world constraints. Key characteristics of wicked problems include:

1. **Ambiguity:** Wicked problems lack clear problem definition, have unclear aims, and therefore cannot be addressed with universally accepted solutions.
2. **Interconnectedness:** These problems span several policy domains and scales, impacting multiple stakeholders and involving overlapping jurisdictions, sectors, and systems.
3. **Competing Values:** Different stakeholders may have conflicting values and interests, and hold divergent priorities, making consensus difficult to achieve.
4. **Unintended Consequences:** Attempts at solving wicked problems frequently produce unforeseen or adverse consequences, requiring ongoing reevaluation and adaptation.
5. **Evolving Conditions:** Wicked problems evolve over time, requiring a tenacious and durable approach to advancing solutions.
6. **No Final Solution:** Rather than being “solved,” wicked problems tend to be managed through sustained, iterative engagement.

In Oklahoma, such problems frequently emerge at the intersection of human activity, technological systems, and the natural environment. The S3OK project focused on those wicked problems that involve interactions between water resources, land systems, atmospheric conditions, and critical infrastructure.

Toward Sustainable Solutions

Initiatives designed to address wicked problems must involve multiple groups that represent a range of different interests. Because wicked problems are persistent and systemic, efforts to

address them must reflect similar tenacity and systemic thinking. Effective strategies must be:

- Long-term in orientation
- Durable across political and economic cycles
- Sustainable in environmental and social terms
- Incremental and adaptive, recognizing the necessity of partial solutions that evolve over time

Equally important is engaging a broad range of stakeholders representing the private sector, public agencies, scientific and technical communities, and civil society. This approach strengthens legitimacy and improves the likelihood that solutions will reflect both technical feasibility and community priorities across a range of actors. Success requires iterative processes, openness to revision, and a pragmatic tolerance for working through disagreement.

Given the complexity of wicked problems, sustainable solutions for Oklahomans must employ the full spectrum of our collective insight and skill sets. Successful strategies are contingent upon collaborations that leave room for substantial revision as stakeholders learn over time from science and experience. A willingness to pursue partial solutions, and a tolerance for and an ability to work around deep disagreements, is also necessary. Overall, a successful approach to addressing wicked problems must be as relentless as the wicked problems we face.

Oklahoma's Unique Context

At the start of this project, Oklahoma was uniquely situated to lead in developing responsive, scalable approaches to wicked problems. Our distinctive combination of natural resources and a longstanding ethic of resilience provided a rich opportunity to coalesce around challenges at the intersection of water, land, and critical infrastructure. The cross-cutting environmental challenges we face provide a robust foundation for applied experimentation with an interdisciplinary approach. Moreover, Oklahoma has fostered a tradition of self-reliance and ingenuity evident in the legacy of managing oil,

gas, and agricultural resources through adaptive governance in resource-intensive contexts.

Importantly, Oklahoma's tradition of multi-stakeholder collaboration—across public, private, and tribal entities—offered a strong platform for assuring that a robust cross-section of stakeholder perspectives and knowledge were included in problem-solving. Local ownership and place-based solutions were critical: sustainable outcomes cannot be externally imposed. Instead, socially sustainable solutions must emerge through processes that are grounded in local contextual expertise and iterative engagement.

The S3OK initiative exemplifies how cross-sector collaboration can be mobilized to tackle wicked problems. Our approach emphasizes incremental, adaptive strategies that are flexible enough to evolve as conditions change over time. S3OK highlights the importance of sustained investment in processes that are inclusive, iterative, and informed by both science and lived experience. In the sections that follow, we describe the core challenges Oklahoma faces and present a framework for responding to them that draws on the state's unique assets and commitment to long-term, socially sustainable change.

Oklahoma's unique blend of natural resources and culture of resilience make it an ideal environment to test and refine solutions for wicked problems.

By cultivating champions from within, fostering collaborative networks, and utilizing our expansive resource base, S3OK seeks to develop and refine responses that are locally effective and globally relevant while serving as a model to others seeking to achieve similar aims.

Socially Sustainable Solutions for Water, Land Use, and Infrastructure (S3OK)

The Socially Sustainable Solutions for Water, Land Use, and Infrastructure Resilience in Oklahoma (S3OK) project was designed to advance science-based assessments of wicked problems, coupled with systematic and iterative engagement with Oklahoma stakeholders, to develop socially sustainable solutions. S3OK's primary objective is to develop and test sustainable solutions for wicked problems at the intersection of the following challenges:

- Changing weather patterns
- Variable water quality and availability
- Land use transitions
- Critical aging infrastructure systems

This chapter focuses on two integrated components of the S3OK project and includes:

1. A summary of the 5-year collaborative research program that focused on land, water, and infrastructure resilience across Oklahoma.
2. A description of the S3OK framework, which distills the core findings and strategies developed through the project into a

practical guide for future planning, policy, and implementation.

The distinguishing feature of S3OK is its emphasis on interaction and iteration. Over the course of five years, researchers and technical experts worked in close coordination with an Opinion Leader Advisory Network (OLAN) to refine priorities and approaches. Rather than advancing siloed science—developed without external inputs—the project embraced ongoing dialogue and co-production of knowledge among scientists from multiple fields, practitioners, and policymakers coupled with a regular input stream from the Oklahoma public. This approach enabled S3OK to surface solutions that reflect both the complexity of the systems involved and the values and constraints of the communities affected by them.

The S3OK approach provides a compelling basis for the identification, modeling, and quantification of solution sets that can be applied to problems facing Oklahoma, the Great Plains, and the nation. The S3OK framework builds from an understanding of how sub-seasonal-to-seasonal (S2S) weather patterns

The Opinion Leader Advisory Network consisted of leaders from Oklahoma's public, private, and nonprofit sectors. OLAN members offered constructive feedback and direction to S3OK researchers on the direction and impact of S3OK research while helping integrate science and policy into strategic solutions for Oklahoma.

affect Oklahoma's water quality and quantity, land use, and critical infrastructure. Researchers hypothesize that sustainable solutions cut across challenge areas and fields of practice, where policy beliefs and preferences are less polarized. Through the S3OK framework, researchers have worked to develop solutions that address these overlapping problems in ways that resonate with Oklahoma's communities and policymakers.

As a result of iterative engagement between scientists and practitioners, over the five-year project, researchers' focus evolved as data and insight were gained from interaction with project stakeholders—including the OLAN, the public, and a scientific advisory network (Figure 1.1). For example, an initial focus on carbon transitioned to a focus on land use over time. After an extensive qualitative and quantitative process of problem identification, narrative enumeration, researchers homed in on three, highly impactful and intersecting problem domains with the potential to have large-scale impacts on the state's future:

- Exploration of Hybrid Treatment and Reuse Alternatives for Wastewater and Stormwater in a Municipal Context
- Enhancing Water Availability for Agricultural and Oilfield Applications
- Natural Hazards and Utility Resilience

The S3OK Project Overview

The S3OK project was designed to foster cross-sector collaboration and expand the capacity of Oklahoma-based researchers and practitioners to tackle complex, interrelated environmental and infrastructure challenges. By breaking down disciplinary silos, the project enabled creative, systems-oriented problem-solving and generated actionable strategies to address the state's most urgent and emerging issues.

Central to S3OK was a commitment to science-informed solutions to wicked problems. Project-affiliated scientists and practitioners collaborated to advance science-informed solutions that could be piloted, assessed, and implemented across contexts. S3OK served as a test bed for developing these solutions, through which innovative ideas were put into practice, assessed, and scaled. The novelty of the S3OK project was in its approach: a social science-led, interdisciplinary collaboration that incorporated the perspectives of competing social narratives to disentangle the numerous current roadblocks that impede the development of effective, socially sustainable solutions to complex problems in Oklahoma. This approach allowed for better definition and development of a shared understanding that is critical for addressing challenges resulting from the interactions of humans with the natural and built environment in Oklahoma.

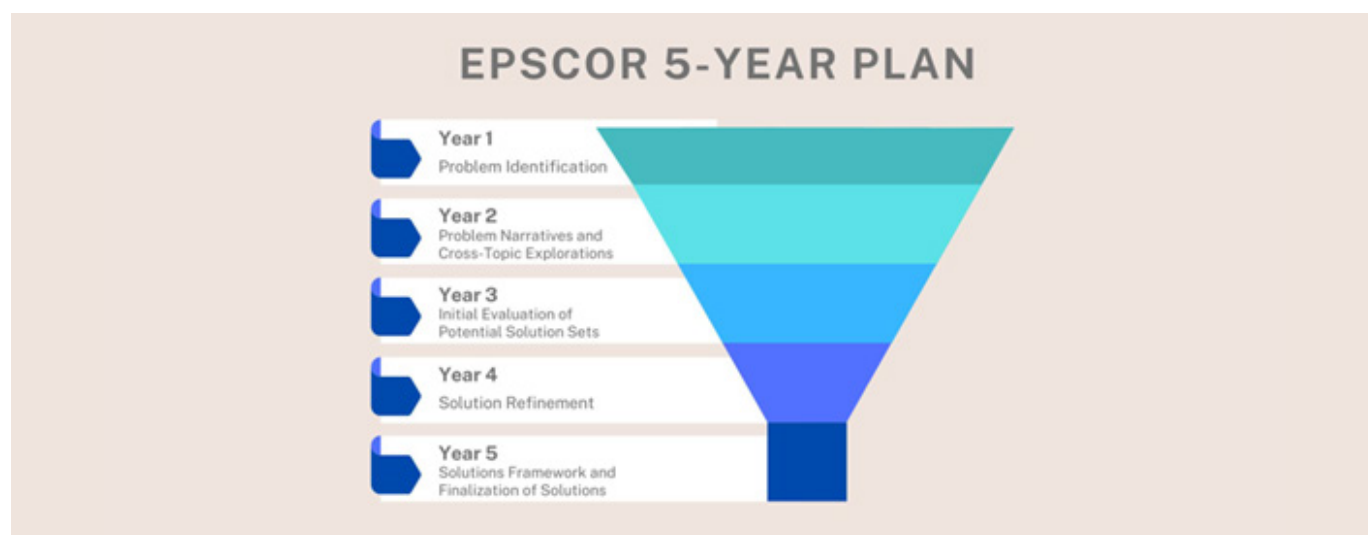


Figure 1.1. Over five years, the EPSCoR project evolved from problem identification to identifying and finalizing solutions.

S3OK prioritized initial problem domains that reflected the complexity and urgency of the challenges that faced Oklahoma and the broader Great Plains. These issues are technically complex, socially contested, and deeply intertwined. They include:

- Shifting seasonal weather patterns and extremes at the subseasonal to seasonal scale
- Increasing variability in water supply, along with rising volumes of marginal-quality water
- Changes in carbon dynamics in and on the Oklahoma landscape—both natural and managed
- Growing threats to the sustainability of the state’s energy, transportation, and water infrastructure systems

Problem focus areas were selected because they addressed an intertwined set of seemingly intractable challenges that are fraught with disagreement. These problem-focus areas are not only environmental—they are also political, economic, and social. In many cases, public debate is shaped by disagreement over the severity of the problems and the viability or fairness of potential solutions. The S3OK approach acknowledges these tensions and works within them, developing strategies that are evidence-based, adaptive, and responsive to stakeholder priorities.

Integrated and Interdisciplinary Approach

The S3OK project applied an integrated social science framework grounded in iterative engagement and empirical analysis to identify how Oklahomans perceive and are willing to respond to science-based solutions for interconnected, high-stakes challenges. Using multiple modes of engagement through annual project-wide meetings and smaller scale focused meetings and working groups, we traced linkages across the project’s focus areas and assessed public acceptance of policy interventions, accounting for Oklahoma’s wide range of value orientations, economic interests, and cultural narratives (Figure 1.2).

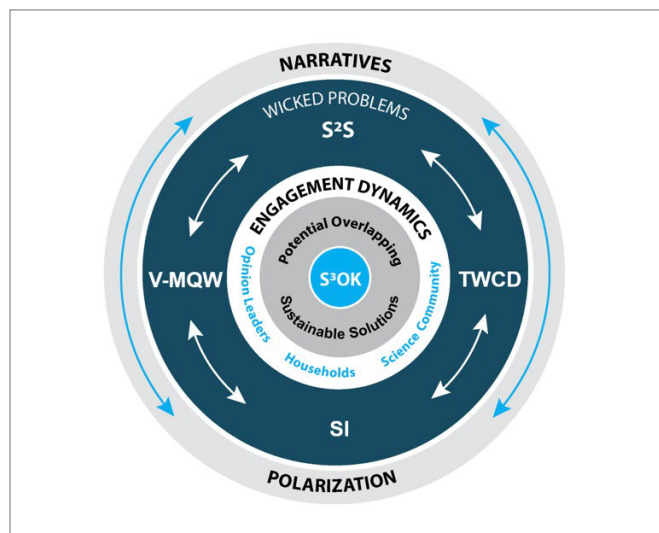


Figure 1.2. The project uses an interdisciplinary approach that applies feedback from opinion leaders and Oklahoma households to focus research on finding sustainable solutions for wicked problems. S3OK focused on wicked problems at the intersection of Subseasonal-to-Seasonal Weather Patterns (S2S), Variable and Marginal Quality Water Supplies (VMQW), Terrestrial Water and Carbon Dynamics (TWCD), and Sustainable Infrastructure (SI) using a Social Dynamics (SD) framework.

The interdisciplinary problem-focus-area science teams explored technical innovations that had a high potential to converge on solutions that cut across competing social narratives that have impeded collective decisions in the past. These innovations aimed to provide pragmatic, science-informed solutions that bridged ideological divides and historical tensions around shared infrastructure, water resources, and land management.

The annual S3OK “Academy” meetings in each of the five years of the project enabled engagement between the focus area teams, the Extended Peer Science Advisory Network (EPSAN), and the Opinion Leader Advisory Network (OLAN), employing modified approaches to civic engagement to iterate in on the most promising and acceptable approaches.

Through these multiple modes of inquiry and engagement, the S3OK project identified scientifically and socially promising shared definitions of problems and science-based solutions for wicked problems, culminating in a consensus report providing a vision and pathway for science-based solutions for wicked problems in Oklahoma (Figure 1.3).

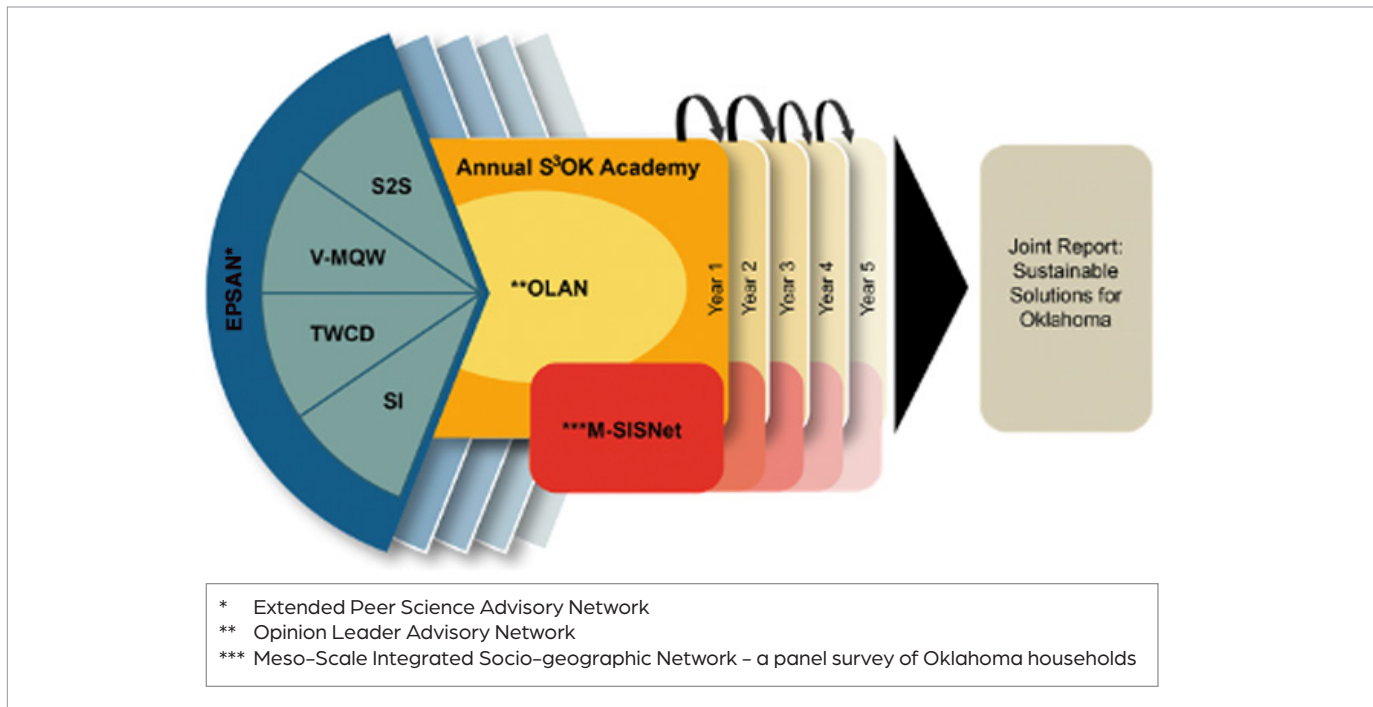


Figure 1.3. Five annual academies provided opportunities for face-to-face interaction between all parties involved, resulting in consensus in direction and results.

Engagement

Changes over time in patterns of sub-seasonal to seasonal (S2S) weather extremes (e.g., increasing rate of shifts between pluvial events and severe drought) have affected Oklahoma's landscape-carbon cycle, water availability and quality, and the resilience of the state's water and energy infrastructure. At the same time, changes in land use, water availability, and infrastructure interact with each other in important ways that affect both scientific understanding of the problem and potential solutions. However, Oklahoma citizens are divided – as are those of the country as a whole – by opposing social narratives about these issues. Our previous research confirmed through data collected from the Meso-scale Integrated Socio-geographic Network (M-SISNet) that conflicting beliefs and value priorities impede the actions required to address the urgent and connected set of water, landscape-carbon cycle, and infrastructure resilience challenges facing Oklahoma today².

The divides across cultural and ideological groups concerning the causes and consequences of these problems are substantial. Wide disparities

are evident between Oklahoma's conservative individualists and liberal egalitarians concerning:

- Anthropogenic causes of climate change
- Adequacy of future water supplies
- Changing frequency of wildfires
- Causes of earthquakes

Similarly, Oklahomans' views concerning potential solutions – e.g., carbon taxes, public investment in sequestration, and imposition of state regulations to manage induced seismicity – all show large divides². Coupling problems with specific sets of prescribed solutions – e.g., restrictive regulations designed to reduce carbon dioxide emissions or induced seismicity – appears to many Oklahomans to be linked to broader ideological beliefs or cultural worldviews that conflict with their own.

This kind of value-driven response, reinforced by competing social narratives, undermines the capacity for accommodating constructive conversations about problems and solutions across cultural divides. The result is interlocking sets of wicked problems that are difficult or impossible to solve because of:

- Incomplete or contradictory knowledge
- A need for further technological innovation
- Diverse and conflicting narratives by which stakeholders make sense of the issue
- The interconnected nature of problems across distinct science and policy domains

Despite persistent wicked problems, there remain areas of agreement, for example, willingness to invest in infrastructure to address water problems³ or to authorize prescribed burns to manage invasive species⁴. Such issues receive substantial support in Oklahoma from both conservative individualists and liberal egalitarians. These domains of agreement that straddle cultural divides illustrate a promising avenue for redefining problems and solutions in ways that permit finding more widely acceptable solutions. This project identified areas of potential agreement that are less entangled in narratives of cultural division to enable the social definition and technical and policy development of acceptable solutions to pressing societal problems.

Framework for Addressing Wicked Problems: A Narrative Overview

Addressing wicked problems requires a structured yet adaptive approach that integrates scientific, social, and policy perspectives. This framework provides a description of the systematic process that underpinned the efforts S3OK researchers took to develop a shared understanding of the problem, collaborate on solution generation, and begin implementing strategies to ensure a holistic response (Figure 1.4).

1. Understanding the Current State of the Problem

The first step in addressing a wicked problem involves identifying its key attributes and understanding the current state of the problem. For the wicked problems S3OK sought to address, this meant analyzing:

- Characteristics that make it wicked (e.g., what are the competing priorities, narratives,

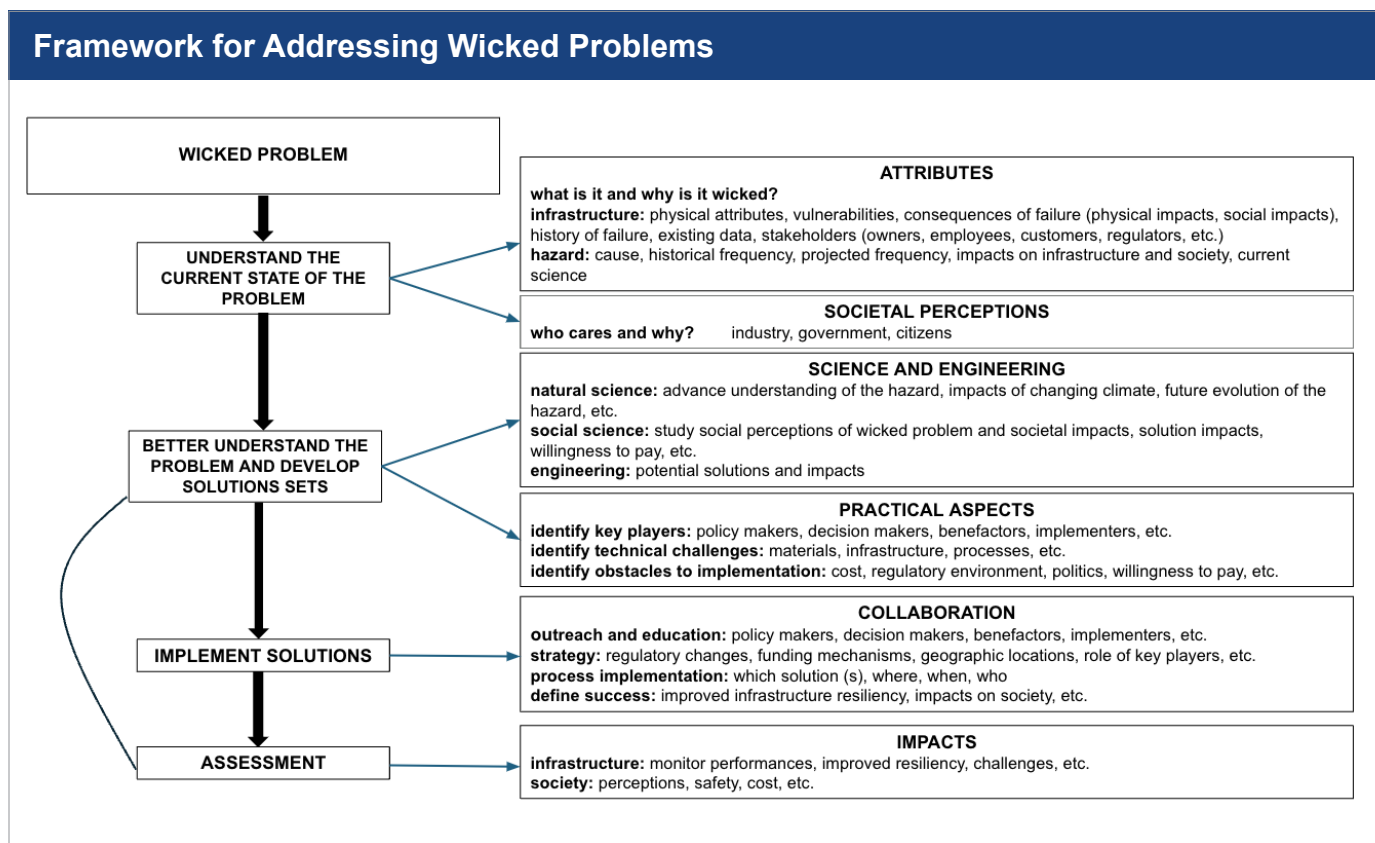


Figure 1.4. Detail of the framework used to address Oklahoma's wicked problems.

and understandings of this problem) and identifying potential points of synergy.

- Physical vulnerabilities and consequences of failure.
- Historical patterns of failure and past responses.
- Societal perspectives including industry, government, employees, customers, and regulators.
- Hazard characteristics, such as natural hazard frequency and intensity and their impacts.

At this stage, assessing societal perceptions of the issue is particularly crucial. Understanding who cares about the problem and why—from industry leaders and government officials to affected (and unaffected) citizens—helps define the urgency and scope of potential solutions.

2. Better Understanding the Problem and Developing Solutions

Once the problem is defined and its current state assessed, it is necessary to develop a deeper scientific and engineering understanding while also considering social and practical factors that influence solution viability. This involves:

- Natural Science Research – Understanding the hazard itself, such as hazard frequency, intensity, predictive abilities within appropriate timescales, and the potential future evolution of these hazards.
- Social Science Research – Studying how people perceive risk, public willingness to support solutions, and the social dimensions of resilience.
- Engineering Solutions – Exploring potential technological advancements to mitigate risks and enhance resilience.

Additionally, we must balance practical aspects and needs alongside the need to develop a deeper scientific and engineering understanding of wicked problems. This includes:

- Identifying key players (e.g., policymakers, decision-makers, infrastructure managers, and implementers).

- Recognizing technical challenges (e.g., materials, infrastructure design, and implementation logistics).
- Assessing barriers to implementation (e.g., cost, regulatory constraints, and political considerations).

3. Implementing Solutions

Effective solutions require collaboration across disciplines and sectors. This stage involves:

- Coordination and outreach – Engaging policymakers, decision-makers, and affected communities.
- Strategic planning – Understanding constraints and opportunities afforded by regulatory frameworks, securing funding, and defining roles.
- Process implementation – Determining who will implement solutions, when, and with what resources.
- Defining success – Establishing metrics to evaluate improved outcomes and how societal impacts are mitigated.

4. Assessing and Measuring Impacts

The final step of this process involves monitoring and evaluating the effectiveness of implemented solutions. This step is variable and contingent upon the unique characteristics of each wicked problem focus area. For example, in the context of Natural Hazards and Utility Resilience, this may include focusing on assessing and measuring impacts to:

- Infrastructure resilience – Measuring performance improvements, system adaptability, and identifying remaining challenges.
- Societal outcomes – Assessing public perceptions of safety, cost-effectiveness, and long-term sustainability.

By following this iterative framework, decision-makers can develop more adaptive, evidence-based responses to wicked problems. This structured yet flexible approach ensures that scientific understanding, engineering

solutions, and policy innovations are effectively integrated to build resilient, future-ready infrastructure systems.

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CHAPTER 2

Research Teams: Key Wicked Problem Focus Areas in Oklahoma



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21	Social Dynamics (SD) Team
22	Changing Subseasonal to Seasonal Weather Patterns (S2S) Team
24	Variable- and Marginal- Quality Water Supplies (V-MQW) Team
26	Terrestrial Water and Carbon Dynamics (TWCD) Team
27	Sustainable Infrastructure (SI) Team
28	References

CHAPTER 2

Research Teams: Key Wicked Problem Focus Areas in Oklahoma

The S3OK research initiative brought together research teams across interrelated domains—Subseasonal-to-Seasonal Weather Patterns (S2S), Variable and Marginal Quality Water Supplies (V-MQW), Terrestrial Water and Carbon Dynamics (TWCD), and Sustainable Infrastructure (SI)—all anchored by a unifying Social Dynamics (SD) group. This integrated structure provided strategic coherence to the five-year effort, ensuring that each team’s work contributed to a comprehensive understanding of the complex, interdependent natural and human systems shaping Oklahoma’s most persistent challenges.

Each focus area addressed high-stakes issues central to Oklahoma’s environmental and economic future: increasing variability in weather patterns, changing water quality and availability, changing patterns of land use, and growing challenges to infrastructure reliability. Historically, addressing these concerns in isolation has exacerbated social divisions and policy gridlock. By approaching them as interconnected, S3OK enabled a reframing of problem boundaries and fostered more constructive dialogue across stakeholder groups. This integrated model also offered a basis for negotiating value tradeoffs—balancing environmental, economic, and social priorities in pursuit of broadly supported, socially sustainable solutions.

Throughout the project, cross-sector collaboration was enriched with inputs from Oklahoma households (via the **M-SISNet**), strategic interdisciplinary exchanges within the EPSAN, and interactions with diverse opinion leaders through the OLAN. This approach created a continuous feedback loop that grounded research in lived realities and policymaking contexts in Oklahoma.

***The Oklahoma Meso-Scale Integrated Socio-Geographic Network (M-SISNet)** is a panel survey of up to 2,500 households across Oklahoma that gathers insights on perceptions of key problem areas, feasibility of solutions, and willingness to support proposed solutions.*

These partnerships allowed the project to:

- Strengthen and enhance interdisciplinary collaboration within Oklahoma’s research institutions
- Push the boundaries for innovative solutions to some of the region’s most persistent societal issues
- Establish a visible testbed for integrating scientific research, community outreach, education, and collaborative problem-solving to address pressing challenges in an increasingly fragmented society.
- Position Oklahoma as a leader in developing and applying science-driven, inclusive solutions to urgent socio-environmental issues

This chapter will introduce the teams working throughout the five-year project and the focus of their research:

- Social Dynamics (SD)
- Changing Seasonal to Subseasonal Weather Patterns (S2S)
- Variable and Marginal Quality Water Supplies (V-MQW)
- Terrestrial Water and Carbon Dynamics (TWCD)
- Sustainable Infrastructure (SI)

Social Dynamics (SD) Team



THE SD TEAM FOCUSED ON PEOPLE'S PERCEPTIONS AND BELIEFS SURROUNDING WICKED PROBLEMS.

The Social Dynamics (SD) team examined the pivotal role of public perceptions and social narratives in shaping Oklahoma's ability to respond to wicked problems. These perceptions influence individual behaviors, collective decision-making, and the broader societal capacity to adapt to emerging threats across infrastructure, water systems, land use, and changing weather patterns. Drawing on data from the M-SISNet, the SD team:

- Measured and modeled the perceptions and beliefs underpinning social narratives that fueled debates among the public, opinion leaders, and scientists about the pressing issues identified in the project's focus areas.
- Evaluated how pervasive narratives hindered collective action toward convergent solutions that recognized the complex human-driven origins of these challenges.

- Assessed social valuation of potential solutions, including willingness to pay for sustainable options.

By providing a structured framework for understanding social dynamics, the SD team facilitated the identification of socially sustainable solutions aimed at Oklahoma's most critical challenges. S3OK's distinct yet interrelated focus areas were used to enhance understanding of overlapping dynamics that drive these issues. The team's objective was to identify overlapping problems and associated solution sets that fostered consensus and constructive engagement and to reframe (or steer clear of) the kinds of divisive narratives that often derail constructive problem-solving. Through this lens, the Social Dynamics team supported the identification of practical solution sets that aligned with public values and institutional capacities, contributing to more resilient governance structures across the state.

The Social Dynamics Team advanced six goals throughout the project:

1. Evaluate and Model Narrative Mechanisms:

The SD team aimed to deeply understand the drivers behind attachment to competing social narratives, particularly how these narratives shape public opinion, influence decision-making, and contribute to social polarization. By analyzing these factors, the SD team sought pathways to reduce tensions and foster more constructive and collaborative discourse around pressing issues in Oklahoma.

2. Collaborate Across Focus Areas:

Recognizing that the project's focus areas are interconnected, the Social Dynamics team worked closely with other teams to ensure that insights from each area informed a holistic approach. This collaboration enabled the integration of diverse perspectives, helping to align strategies for addressing complex and intersecting challenges.

3. Leverage New Research: Utilizing data from the M-SISNet, EPSAN, and OLAN, the team employed advanced analytic methods to capture evolving public sentiment across different Oklahoma stakeholder groups (the public, scientists, and opinion leader practitioners), enabling the refinement of engagement strategies and solution design in near real-time.

4. Support Inclusive Problem Definition:

Through robust data collection and analysis, the team sought to develop more inclusive and nuanced problem definitions that considered the diverse experiences and perspectives of Oklahoma's communities. This inclusivity was aimed at fostering a comprehensive understanding of issues that would resonate with and engage a broader range of stakeholders.

5. Systematically Evaluate Solution Sets:

The team conducted a rigorous evaluation of potential solutions, assessing each for practical feasibility, long-term sustainability, and social acceptance. This goal was essential for identifying solutions that not only addressed technical aspects but also aligned with community values and were adaptable to Oklahoma's diverse needs.

6. Assess Sustainable Policy Mechanisms: By studying policy mechanisms, the team aimed to identify approaches that could realistically implement socially sustainable solutions to wicked problems. This involved assessing policy durability, stakeholder buy-in, and environmental impact to ensure that selected policies supported resilience and sustainability in Oklahoma's communities.

Changing Subseasonal to Seasonal Weather Patterns (S2S) Team



THE S2S TEAM FOCUSED ON CHANGING WEATHER PATTERNS AND THE WICKED PROBLEMS ARISING FROM THOSE CHANGES.

The S2S Team addressed the shifting weather patterns driving transformation across both natural and human systems in Oklahoma (**Figure 2.1**). These subseasonal to seasonal shifts, occurring on scales of 10–90 days, included fluctuations in average and extreme precipitation

and temperature. With such changes arising in the context of competing social narratives about the impacts of human activity on the climate, recognizing and responding to these evolving S2S patterns presented unique challenges. To address these changing weather patterns, the S2S focus

area team conducted comprehensive research to:

- a. Deepen understanding of the atmospheric and land processes driving changes in S2S patterns
- b. Refine models and improve the predictability of S2S events
- c. Generate critical data for managing Oklahoma's water, carbon, and infrastructure systems

By advancing basic science and predictive capabilities around S2S events, the team aimed to support Oklahoma opinion leaders (through the OLAN) and households (via M-SISNet) in developing socially sustainable solutions to the increasingly frequent and diverse threats impacting communities across the state. The primary objective of the S2S team was to improve knowledge of S2S-related atmospheric and land processes and enhance predictive accuracy, ultimately enabling the development of outlook forecasts that could better equip Oklahomans to respond to and manage climate-related risks.

Throughout the project, the S2S team advanced five goals:

- **Enhance Knowledge of Atmospheric and Land Processes:** The S2S team aimed to deepen understanding of the atmospheric and land processes driving subseasonal to seasonal (S2S) events in Oklahoma, with particular attention to "weather whiplash" events. This research provided insights into the mechanisms contributing to changes in precipitation and temperature patterns and identified factors that impact predictive accuracy in the region.
- **Improve Predictive Skill for S2S Events:** The team worked to improve forecasting models, enabling the development of "outlook" forecasts for S2S events that included measures of certainty. These advances offered Oklahoma communities and stakeholders tools for more reliable weather projections and future preparedness.
- **Support Cross-Domain Data Sharing and Utilization:** Data from S2S outlook forecasts

generated throughout the project were integrated across team collaborations with TWCD, VMQW, SD, and SI groups. These data sets and insights provided valuable S2S context that underlies cross-cutting challenge areas while informing modeling of water availability, infrastructure vulnerability, wildfire risk, and land management strategies.

- **Engage with Focus Areas to Address Infrastructure, Water, and Land Needs:**

By working with other focus area teams, the S2S team contributed to an integrated understanding of infrastructure, water, and land use challenges in Oklahoma. This collaboration enhanced the capacity for addressing the impacts of S2S events on these critical systems.

- **Provide Inputs for Socially Sustainable Solutions Modeling:** S2S outcomes delivered essential inputs to the social dynamics team, supporting their work in modeling potential socially sustainable solutions at the intersections of land use, water availability, and infrastructure. These results laid a foundation for community-driven strategies to navigate and mitigate Oklahoma's climate challenges.

Variable- and Marginal- Quality Water Supplies (V-MQW) Team



THE V-MQW TEAM FOCUSED ON WICKED WATER PROBLEMS SUCH AS WATER AVAILABILITY AND DEMAND.

The V-MQW focus area addressed issues surrounding Oklahoma's water demands, which are projected to increase by 600,000 acre-feet per year between 2007–2060¹. Reliable water supplies are needed to provide for these demands while meeting the state's goal of capping freshwater use to 2010 levels.

However, freshwater supplies are declining due to reservoir sedimentation and groundwater overdraft and are increasingly vulnerable to S2S variability². Concurrently, volumes of oil and gas "produced water," municipal wastewater, and stormwater are increasing with continued oil and gas development and urbanization. Disposal of produced waters has been correlated with seismicity, potentially impacting infrastructure and resulting in energy production curtailment in some regions.

Marginal-quality water (MQW) refers to water of lower quality than fresh, potable water but can still be used for certain purposes with appropriate management and precautions. In Oklahoma, source of MQW include stormwater runoff, produced water from oil and gas, and treated wastewater.

The challenge is finding a mix of solutions that allow Oklahoma's diverse array of **marginal-quality waters (MQW)** to be economically treated for beneficial use to address S2S-related water scarcity, waste disposal, and

infrastructure risk while supporting continued energy production and economic growth. Moreover, water treatment solutions must also receive broad support from relevant stakeholders and elicit wide-ranging support from the public

for implementation across Oklahoma's diverse water systems.

Our researchers hypothesized that the quality of Oklahoma's MQW can be improved by developing and deploying solutions based on chemical, biotechnological, hydrological, engineering, and sociological principles, with a focus on expanding opportunities for MQW reuse. The reuse of MQW has the potential to provide substantial quantities of water for the industrial, energy, agricultural, and municipal sectors, making communities and economies more resilient to increasing S2S variability.

Quantities of MQW are estimated to far exceed consumption in Oklahoma, which makes it a vast, under-tapped resource if it can be handled safely. The V-MQW Team therefore focused initial efforts on addressing the following uncertainties:

- What happens to the leftover pollutants in MQW trace pharmaceuticals, hydrocarbons, and other emerging chemicals)? What risks do they pose, and how can they be removed?
- What is the level of public, industry, and regulatory acceptance of using reclaimed water?
- What are the energy and carbon footprints and related economic costs associated with conventional and new, innovative water treatment systems?
- What are the impacts of S2S variability on the infrastructure and operations of reuse systems?

In response to these uncertainties, the V-MQW team's objective was to develop new natural and engineering technologies and modeling schemes for more effective reuse. By extension,

this generated an improved understanding of water treatment efficiencies, which are beneficial to utility end users. Throughout the project, the V-MQW team sought to advance three key goals:

1. Identify Sustainable Treatment Solutions:

The V-MQW team explored innovative active, passive, and hybrid treatment systems for stormwater, wastewater, and produced water to address the competing interests surrounding the use of MQW. This exploration sought to uncover socially sustainable solutions that balanced the needs of different stakeholders.

2. Develop Advanced Treatment Technologies and Models:

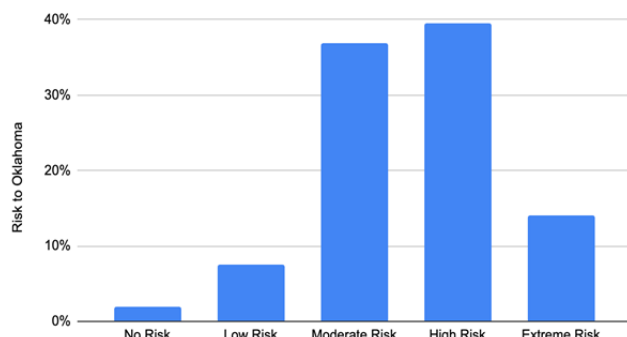
V-MQW research led to the development of state-of-the-art basic science and natural and engineered

technologies, along with advanced modeling schemes that advanced understanding needed to consider water reuse practices. These advancements contributed to more effective strategies for treating and reusing water resources.

3. Improve Understanding of Treatment Efficiencies:

V-MQW research provided key insights into the efficiencies of different treatment methods, focusing on factors such as contaminant fate and removal, flow rate, energy use, and carbon emissions. These findings offered valuable guidance for utility sectors, policymakers, regulators and end-users. They also supported more informed system designs, technology and program decisions, and risk communication regarding water management practices.

How much risk does Eastern Red Cedar encroachment pose to the state of Oklahoma?



How much risk does Eastern Red Cedar encroachment pose to you?

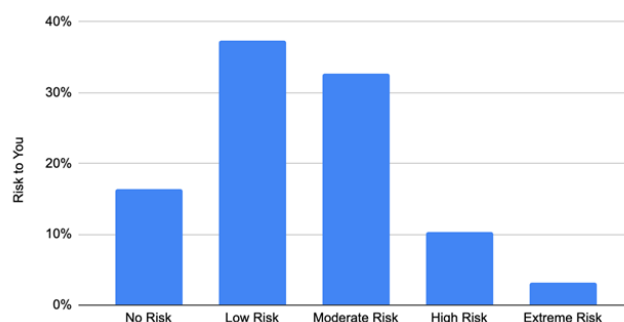


Figure 2.1. Results from Wave 4 survey of the M-SISNet focused on the public's concern about land management in Oklahoma.

Terrestrial Water and Carbon Dynamics (TWCD) Team



THE TWCD TEAM COLLECTED DATA REGARDING WICKED PROBLEMS AFFECTING LAND MANAGEMENT, A CENTRAL FOCUS OF THE S3OK PROJECT. THIS TEAM WAS ALSO A CRUCIAL LINK BETWEEN OTHER PROJECT DOMAINS WHICH OFTEN OVERLAPPED.

The TWCD (Terrestrial Water and Carbon Dynamics) focus area was central to addressing the complex problems within the S3OK project scope, particularly due to conflicting policy narratives surrounding carbon management and the impacts from various land management practices, such as increased risk of impacts from wildfire. This focus area played a pivotal role by fostering linkages with other project domains, creating opportunities for engaging key stakeholder groups in discussions aimed at both defining these critical problems and identifying potential sustainable solutions. The interplay between land use and carbon cycle issues was especially important since terrestrial ecosystems and the cycling of carbon and water were integral to the broader environmental and infrastructural challenges addressed in the S3OK project.

The primary objective was to collect and calibrate essential data to inform management decisions that could impact ecosystem productivity, carbon storage, and water yield for agricultural, municipal, industrial, and ecological purposes (**Figure 2.1**). These insights helped shape strategies for managing Oklahoma's land and water resources in a way that balanced competing demands while enhancing long-term sustainability.

The TWCD team worked to advance four primary goals throughout the project:

1. Inform Stakeholders on Carbon and Water Dynamics:

The Land/Water Observatory and Land/Water forecasting efforts associated with TWCD were designed to inform Oklahoma households (via M-SISNet), the peer science advisory network (EPSAN), and Oklahoma opinion leaders (OLAN) about new ways to

understand broad-scale carbon and water dynamics as they relate to climate change and resource management.

2. Inform Stakeholders on the Impacts of Land Use and Climate Management Decisions:

Insights from TWCD research provided a deeper understanding of the mechanisms underlying ecosystem carbon and water dynamics, as well as the tradeoffs involved in managing these resources. These results addressed globally relevant scientific questions and helped calibrate the Land/Water Observatory initiatives. The process and outcomes also informed diverse stakeholders about how land-use and climate-management decisions impacted ecosystem productivity, carbon storage, and water availability for agricultural, municipal, industrial, and ecological uses.

3. Support Sustainable Water and Carbon Management:

The tradeoffs identified in these studies became essential inputs for shaping socially sustainable solutions focused on water use, reuse, and carbon reduction. Given the significant footprint of grazing and cropland in Oklahoma, it was important to understand how different management strategies affected soil carbon and water. These results were modeled for different plant species and systems to inform predictive models (Earth-system, crop, economic, and others), guiding future land-use decisions.

4. Develop Models that Balance Economic, Environmental, and Social Needs:

TWCD research fed insights developed throughout the project into models designed to balance

long-term economic, environmental, and social needs through socially sustainable solutions. Recognizing that strategies increasing soil carbon sequestration might also enhance soil water-holding capacity and agricultural productivity, the scenarios

developed for climate, water management, and agriculture provided stakeholders with critical information to reframe complex challenges. This helped alleviate social barriers, moving stakeholders closer to essential solutions.

Sustainable Infrastructure (SI) Team



THE SI TEAM FOCUSED ON HOW WICKED PROBLEMS AFFECT WATER AND ENERGY INFRASTRUCTURES.

The Sustainable Infrastructure (SI) team aimed to advance a comprehensive understanding of how Oklahoma's interdependent water and energy infrastructures were affected by severe weather and subseasonal-to-seasonal (S2S) extremes throughout the project. This includes events within and outside of the subseasonal-to-seasonal scale, such as pluvial events (periods of extreme precipitation) and droughts. The SI Team, in tandem with the TWCD Team (see above), also focused on important carbon cycle dynamics (including changing land use and increasing wildfires), and evolving water management/reuse practices (encompassing both surface and subsurface systems, and accounting for changes in storage and pipeline capacities).

The objective of the SI team was to construct an aggregated resilience model that captures the effects of stakeholder decision-making on the functionality and interconnectivity of Oklahoma's critical infrastructure systems. By developing an aggregated resilience model, this research provided critical insights into the interactions between these factors, offering a foundation for devising a broad spectrum of solutions that strengthened infrastructure resilience across the key project domains: weather, water, and land use. The model also supported the creation of socially sustainable strategies to enhance the state's resilience.

The SI research team had four overarching goals

throughout the project:

1. **Advance Understanding of Infrastructure Vulnerabilities:** The SI team used the results from the S2S, V-MQW, and TWCD teams' modeling efforts, along with recorded and projected data on induced seismicity in Oklahoma, to assess the effects of and uncertainties surrounding severe weather events, S2S extremes, wildfires, and induced seismicity on both current and future infrastructure components. This included analyzing critical elements such as individual pipelines, transmission towers, bridges, and broader infrastructure networks (water, electric power grid, transportation), as well as the interdependencies between these networks.
2. **Develop an Aggregated Resilience Model:** The SI team developed an aggregated resilience model to integrate these insights, highlighting how the combined impacts of weather extremes, environmental hazards, and infrastructure interdependencies influenced the overall resilience of Oklahoma's systems. This model was a key tool for understanding how interdependent infrastructure systems responded to current and future disruptions.
3. **Incorporate Stakeholder Decision-Making:** The project characterized how the decision-making behaviors of diverse Oklahoma

stakeholders affected the performance and resilience of interdependent infrastructure systems. It explored how different stakeholder priorities and choices influenced infrastructure functionality and the development of sustainable solutions.

4. Formulate Socially Sustainable Solutions: The aggregated resilience model was used to design solutions that were not only technically viable but also socially sustainable. These solutions aimed to enhance the long-term resilience of Oklahoma's interconnected infrastructure systems, ensuring they could withstand and recover from future challenges while accounting for social equity and environmental sustainability.

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CHAPTER 3

S3OK Project Objectives, Goals, and Methodology



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32	Original Objectives
33	Objective 1: Deepen Scientific Understanding Across Focus Areas
36	Objective 2: Improve Engagement and Collaboration
36	Objective 3: Identify Socially Sustainable Solutions
37	Goals
37	Strengthening Interdisciplinary Collaboration
37	Advancing Creative, Science-Informed Solutions
38	Establishing a Test Bed for Solutions
38	Training Future Leaders
38	Creating a Network of Champions
38	Methodology
38	Jenkins–Smith (1990): Democratic Politics and Policy Analysis
38	Sabatier and Jenkins–Smith (1993): Advocacy Coalition Framework (ACF)
39	Shanahan, Jones, McBeth and Radaelli (2018): The Narrative Policy Framework (NPF)
39	Jenkins–Smith and Weible (2025): Expanded and Updated ACF
39	Methods for Collecting Data
41	Potential for Agreement and Refining Solutions
41	Produced Water Reuse Potential for Oilfield and Agricultural Applications
41	Novel Hybrid Treatment and Reuse Options for Stormwater and Municipal Wastewater
42	Natural Hazards and Utility Resilience
42	References

CHAPTER 3

S3OK Project Objectives, Goals, and Methodology

Over the past five years, the S3OK project evolved to sharpen its focus while remaining firmly committed to its original goals and relevance. This chapter outlines the project's initial objectives, goals, and methodology. It also embeds an overview of the iterative process throughout and addresses how S3OK researchers leveraged insights from the Extended Peer Science Advisory Network (EPSAN), Opinion Leader Advisory Network (OLAN), and the Meso-scale Integrated Socio-geographic Network (M-SISNet) to strategically refine its efforts over time. This approach enabled S3OK researchers to address a set of three high-impact challenges—areas identified as having strong **Potential for Agreement and Refining Solutions** across sectors and communities in Oklahoma. These areas now anchor the work of S3OK's interdisciplinary teams and serve as the foundation for actionable, science-informed solutions designed to meet Oklahoma's most pressing environmental and infrastructural needs.

Original Objectives

S3OK was launched to tackle “**wicked problems**” at the intersection of **land use, water availability, and infrastructure resilience** in Oklahoma. These problems are marked by complexity, uncertainty, and competing stakeholder interests. The project's central task has been to develop and test science-based solutions that can meet these challenges head-on through an integrated and interdisciplinary approach. Underlying this task is a central, unifying research question: *Can science-*

We asked:

Can science-based assessment of wicked problems, coupled with input and feedback from Oklahoma opinion leaders and the public, result in the development of socially sustainable solutions?

Spoiler: The answer is yes.

based assessment of the intersections of wicked problems, coupled with systematic and iterative engagement with Oklahoma opinion leaders and input/feedback from members of the Oklahoma public, result in the development of socially sustainable solutions?

Our working hypothesis was that socially sustainable solutions would be found at the intersections of related but distinct problem areas,

where a broad range of stakeholders could find agreement because the array of issues cut across the usual narratives that frame social conflict.

To realize our mission, S3OK researchers pursued three overarching objectives:

- **Deepen scientific understanding across five integrated focus areas initially identified by S3OK researchers**

S3OK grounded its work in research across domains where scientific insights and policy relevance intersect and have the potential to positively impact day-to-day decisions for communities and leaders across Oklahoma. These include areas that were the foundation for cross-disciplinary research:

- Subseasonal to seasonal (S2S) weather, water availability, and stormwater runoff management
- Economic and environmental applications for produced water reuse
- Marginal water quality and reuse
- Shifting subseasonal to seasonal weather patterns and wildfire threat
- Reliable interdependent infrastructures

- **Improve engagement and collaboration among key stakeholders**

Socially sustainable solutions require more than good science—they require relationships, feedback, and trust. S3OK researchers developed multiple engagement platforms to ensure that policy, community, and industry voices shaped the work and informed priorities throughout the project lifecycle.

- **Identify socially sustainable solutions to challenging problems within the five integrated focus areas**

S3OK researchers placed a strong emphasis on identifying strategies that are scientifically sound, publicly supported, and institutionally feasible. By working at the intersection of technical innovation and social engagement, S3OK researchers created a pathway for the development of durable solutions that reflect Oklahoma values and realities.

Objective 1: Deepen Scientific Understanding Across Focus Areas

Recognizing the interconnected and variable nature of the challenges S3OK sought to address, one of the project's primary and original objectives was to deepen scientific understanding across five integrated areas identified prior to the project's inception. These included:

- Subseasonal to seasonal (S2S) weather, water availability, and stormwater runoff management
- Economic and environmental applications for produced water reuse
- Marginal water quality and reuse
- Shifting subseasonal to seasonal weather patterns and wildfire threat
- Reliable interdependent infrastructures

While these five domains were selected as foundational areas based on initial interdisciplinary scoping and research priorities, the emphasis of each evolved over time in response to engagement with the S3OK Opinion Leader Advisory Network (OLAN). The input gathered from OLAN facilitated place-based insight, helping refine questions and adjust emphasis to align with local practitioner needs, knowledge gaps, and feasible applications. Across all five areas, the project remained committed to advancing scientific understanding, while OLAN feedback helped to shape more actionable, regionally grounded applications of that science. This dynamic process ensured that each focus area remained integral to S3OK, even as emphases shifted to better meet the evolving priorities of stakeholders across Oklahoma.

Initial Integrated Focus Area 1: Subseasonal to Seasonal (S2S) Weather, Water Availability, and Stormwater Runoff Management

Oklahoma faced, and continues to face, increasingly extreme shifts in subseasonal to seasonal (S2S) weather patterns—rapid swings between drought and pluvial events—that result in both acute water shortages and damaging surpluses. While federal regulations require

municipalities to implement stormwater utilities to manage runoff, public resistance to the design, funding mechanisms, and long-term value of these programs has often stalled their adoption. This lack of posed a significant challenge the development of essential infrastructure. However, integrating solutions that couple water surges with reuse strategies—such as surface water storage or aquifer recharge—may offer a more compelling path forward. By addressing both shortages and surpluses in tandem, these approaches open the door for broader coalitional support.

This focus area presented an opportunity to deepen scientific understanding across multiple focus areas, including Subseasonal to Seasonal Weather (S2S), Variable and Marginal Quality Water Supplies (V-MQW), and Sustainable Infrastructure (SI). By drawing connections between extreme weather variability, water management technologies, and infrastructure readiness, researchers and decision-makers could develop strategies that reflect both technical feasibility and social acceptability. This approach was essential for identifying science-informed pathways that transcend traditional divides and responding directly to Oklahoma's shifting weather patterns and water realities. **The goal here was to help Oklahoma communities build systems that are ready for Oklahoma's weather extremes and supported by the people they serve.**

Initial Integrated Focus Area 2: Economic and Environmental Applications for Produced Water Reuse

At the onset of the S3OK project, Enhanced oil recovery (EOR) operations were a significant economic consideration for oil-producing states like Oklahoma. While hydrocarbon extraction contributes to greenhouse gas (GHG) emissions, EOR presented a strategic opportunity to address multiple challenges simultaneously. EOR processes can both enhance production and support carbon sequestration by injecting CO₂ into depleted formations—effectively reducing net emissions. Simultaneously, EOR operations could offer a pathway to reuse “produced water,” a byproduct of oil and gas activities that has

been linked to induced seismicity when reinjected without sufficient safeguards. By developing and deploying innovative methods for carbon storage and produced water reuse through EOR, Oklahoma could lead in creating technologies with dual economic and environmental benefits. These included immediate emission reductions, safer produced water disposal at depths that mitigate seismic risks, and the foundation for future commercial applications in carbon capture and storage.

The convergence of challenges concerning carbon emissions, water reuse, and seismic safety underscores the importance of deepening scientific understanding across focus areas such as Terrestrial Water and Carbon Dynamics (TWCD), Variable and Marginal Quality Water Supplies (V-MQW), and Sustainable Infrastructure (SI). By advancing research that links these domains, Oklahoma could evaluate how previously distinct challenges become interlocking solutions. This integrated understanding supports the development of targeted policies and infrastructure investments that align with state energy goals while addressing long-term sustainability and risk mitigation. **This work connected science with policy, with the goal of helping Oklahoma position itself as a leader in sustainable energy practices that balance growth with environmental responsibility.**

Initial Integrated Focus Area 3: Marginal Water Quality and Reuse

Throughout the S3OK project Oklahoma faced increasing water scarcity and variability in water quality, the pressure to expand water reuse strategies has intensified. These challenges in water quality and quantity persist, as do public narratives that reused water is inherently unsafe for human consumption. This perception limits both policy support and investment in scalable water reuse infrastructure. Reframing the challenge to focus on how Oklahoma will meet its future water needs, particularly as a growing portion of available supplies are of marginal quality, can shift the conversation. Doing so opens the door for investments in fit-for-purpose treatment systems that combine natural/

passive and active/high-pressure technologies, calibrated to specific end-use requirements such as agriculture, industrial use, or non-potable urban applications.

Addressing this challenge requires deepening scientific understanding across the Subseasonal to Seasonal Weather (S2S), Variable and Marginal Quality Water Supplies (V-MQW), and Sustainable Infrastructure (SI) focus areas. Scientific insight into water quality variability and treatment efficacy enables decision-makers to assess and communicate risks more effectively. This interdisciplinary research was critical to developing socially acceptable and technically viable water reuse systems that can adapt to Oklahoma's evolving environmental conditions while addressing long-standing public concerns.

Work in this focus area enabled decision-makers to evaluate options that are safe, cost-effective, and aligned with public values while building support for the infrastructure investments needed to move reuse from theory to practice.

Initial Integrated Focus Area 4: Shifting Subseasonal to Seasonal Weather Patterns and Wildfire Threat

Throughout the S3OK project, wildfires represented an escalating threat across Oklahoma, driven by the combination of intense rainfall events (pluvials) followed by drought that generates abundant and highly flammable vegetation. Recent fire seasons have placed increasing strain on both agricultural producers and urban communities, disrupting livelihoods, endangering infrastructure, and degrading water quality.

Beyond their immediate impacts, wildfires can significantly alter the state's landscape carbon balances, exacerbate runoff contamination, and weaken infrastructure systems already vulnerable to climate extremes. Recognizing the growing risk offers an opportunity to engage stakeholders around the development of socially sustainable solutions for water and land-use practices, especially when framed as essential to protecting valued ways of life such as rural traditions, land-based economies, and community safety.

Responding effectively to this challenge area requires deepening scientific understanding across S3OK domains including Subseasonal to Seasonal Weather (S2S), Terrestrial Water and Carbon Dynamics (TWCD), Variable and Marginal Quality Water Supplies (V-MQW), and Sustainable Infrastructure (SI). **The goal here was to advance fire resilience strategies that protect community safety, land-based economies, and Oklahoma's environmental assets before disaster strikes.**

Initial Integrated Focus Area 5: Reliable Interdependent Infrastructures

Reliable infrastructure systems are foundational to Oklahoma's economic vitality, public safety, and environmental well-being. They are also essential to national security. These systems—ranging from water and energy to transportation and wastewater—are deeply embedded within social institutions, cultural values, and organizational structures. Today, in Oklahoma, they face mounting stress from multiple, overlapping hazards, including more frequent and severe weather events, wildfires, and seismicity. S3OK's work addresses the resilience of these interdependent infrastructures, including oil and gas, potable and wastewater systems, transportation networks, and the electric power grid. As communities navigate tradeoffs in resilience investments such as where to harden infrastructure or how to prioritize limited resources there is also a need to address the social and political tensions that arise when infrastructure decisions intersect with conflicting public narratives.

This challenge highlights the importance of deepening scientific understanding across Subseasonal to Seasonal Weather (S2S), Variable and Marginal Quality Water Supplies (V-MQW), and Sustainable Infrastructure (SI) focus areas. By integrating physical systems research with insights into public values, institutional behavior, and governance capacity, S3OK supports the development of resilience strategies that are both technically sound and socially feasible. This approach enables Oklahoma decision-makers to identify overlapping risks, assess the consequences of inaction, and design coordinated

solutions that reflect both infrastructure needs and the communities they serve. **This resulted in strategies that reduced risk, stretched limited resources, and reflected the real-world needs of Oklahoma communities.**

Objective 2: Improve Engagement and Collaboration

Engagement and collaboration are necessary precursors to developing sustainable solutions to wicked problems. Throughout the period of performance, S3OK researchers utilized diverse strategies and pathways to foster engagement and collaboration among key stakeholders (**Figure 3.1**). This included a 5-year process to refine the focus to three final wicked problem area that had strong **Potential for Agreement and Refining Solutions**. Part of this process of refinement included participation in important milestone gatherings:

- Annual **Research Retreats** brought together interdisciplinary teams to coordinate science, align research efforts, and plan collaborative opportunities.
- Annual **State Conferences** opened space for sharing breakthroughs and connecting research to real-world problems, inviting broad participation from partners across sectors when appropriate.
- Annual **S3OK Academies** served as invitation-only gatherings of key stakeholders—including

business leaders, utility operators, municipal officials, tribal representatives, and scientists—to collaborate on the direction of S3OK research and emerging policy needs.

- Focus group style **Deep Dive Discussions** in year three offered a targeted forum for tackling specific issues raised by stakeholders leading to sharper problem definitions and cross-sector learning.
- Three **Working Groups** in years four and five formalized collaboration around three major challenge areas, creating a platform for joint action among scientists, industry, and policy leaders (**Figure 3.2**).

Objective 3: Identify Socially Sustainable Solutions

Through the engagement and collaboration process outlined above, S3OK honed in on three critical wicked problem challenge areas that emerged as having strong **Potential for Agreement and Refining Solutions** for implementation across Oklahoma. These areas formed the basis for the Working Groups and were identified at the intersection of five previously established integrated focus areas, reflecting a careful synthesis of insights gained from Deep Dive sessions, direct collaboration with the EPSAN network, input from OLAN, and public opinion data gathered through the M-SISNet. This multifaceted approach ensured that the selected challenges were rooted in interdisciplinary understanding



Figure 3.1. Annual retreats, conferences, academies, and other meetings allowed face-to-face collaboration.



Figure 3.2. Working groups formed to address identified wicked problem areas.

and were informed by diverse stakeholder perspectives.

The process of identifying these challenge areas emphasized the importance of integrating research findings with practical needs and stakeholder priorities through touchpoints embedded in programming at the Academies, Deep Dives, and Working Groups. EPSAN and S3OK researchers provided scientific advances and technical insights shared throughout the annual state conference and research retreat programming. At the same time, OLAN contributed grounded, community-focused perspectives that highlight the unique challenges faced across Oklahoma.

Additionally, public opinion data from the M-SISNet offered a critical and contextualizing lens into the perceptions, needs, and concerns of Oklahoma residents across challenge areas. Researchers leveraged insights from the M-SISNet, alongside feedback from the OLAN, to ensure that the identified challenges and prospective solutions developed resonated with public priorities and needs.

These working groups were designed to foster broad-scale collaboration and coalescence, bringing together researchers, policymakers, and community members to co-develop actionable strategies. The synthesis of inputs from multiple sources not only sharpened the focus on challenges the working groups sought to address, but also provided the foundation for scalable, evidence-based solutions. This collaborative process positions S3OK to address pressing environmental and infrastructural challenges across the state.

Goals

The initial overarching goals of S3OK were to foster innovation, collaboration, and leadership to address Oklahoma's most pressing environmental and infrastructural challenges. By aligning these efforts, S3OK has become a leader in advancing science-informed sustainable solutions while cultivating an innovative, collaborative, and sustainable research ecosystem.

These goals are achieved through:

- Strengthening interdisciplinary collaboration
- Advancing creative, science-informed solutions
- Establishing a test bed for solutions
- Training future leaders
- Creating a network of advocates

Strengthening Interdisciplinary Collaboration

S3OK researchers deepened collaboration across disciplines by facilitating meaningful engagement among researchers, practitioners, and stakeholders. To do so, S3OK researchers integrated public policy learning theories which informed the development of a three-pronged collaborative structure and process carried forth through the project culminating in S3OK's collaborative framework. This collaborative framework integrates diverse perspectives and expertise to address complex challenges.

Advancing Creative, Science-Informed Solutions

By routinely gathering stakeholders at Academy meetings and "Deep Dive" conversations, S3OK researchers listened to their ideas, reflected on them, and adjusted course in real time. This

It was critical to integrate research with the practical needs identified by Oklahomans.

feedback loop fueled science-based, practical fixes to real-world problems and pointed the project toward its next steps.

Establishing a Test Bed for Solutions

Key challenge areas identified through collaborative processes served as focal points for implementing and evaluating research-driven strategies, demonstrating their relevance and scalability in addressing critical issues. Through the M-SISNet, S3OK researchers received input from the public for assessing public perception of developed solutions. Using these inputs, by Year 3 in the project, S3OK researchers further established a testbed for solutions that were collaboratively assessed and refined by project stakeholders including EPSAN and OLAN.

Training Future Leaders

S3OK researchers empowered the next generation of scholars by meaningfully involving students in research and engagement activities. Student researchers advanced cutting edge science in collaboration with scholars and practitioners across the S3OK network, led their own professional development programming, and actively engaged in all S3OK initiatives. This provides hands-on experience and fosters leadership in interdisciplinary problem-oriented research and applications.

Creating a Network of Champions

Through engagement with OLAN, students, researchers, and practitioners, S3OK researchers built a robust network of champions for both the process and outcomes of the S3OK project. These champions sustain and expand the impact of its solutions across academic, professional, and community contexts.

Methodology

S3OK drew upon the Advocacy Coalition Framework public policy theory to guide our approach to advancing socially sustainable solutions. These theories emphasize that long-

term change happens when evidence and collaboration help coalitions adapt and refine their beliefs and priorities, and find common ground despite continuing areas of disagreement. Our working hypothesis was that socially sustainable solutions for wicked problems are found at the intersections of related but distinct problem areas, where diverse stakeholders can find agreement because the array of issues cut across the usual narratives that frame social conflict.

We developed a new, innovative way to identify socially sustainable solutions to wicked problems by leveraging the Advocacy Coalition Framework

These public policy learning theories included:

1. Jenkins-Smith (1990)¹: Democratic Politics and Policy Analysis
2. Sabatier and Jenkins-Smith (1993)²: Advocacy Coalition Framework (ACF)
3. Shahan, Jones, McBeth, and Radaelli (2018): Narrative Policy Framework (NPF)
4. Jenkins-Smith and Weible (2025)³: Revised and expanded Advocacy Coalition Framework (ACF)

Jenkins-Smith (1990): Democratic Politics and Policy Analysis

Public policy learning takes place, and shifts in policy occur, when groups of people with shared beliefs, called advocacy coalitions, push for new policies. These coalitions can include policymakers, researchers, and activists who have worked together over time. They learn from experiences, scientific evidence, and debates to improve their strategies and influence policy decisions. **S3OK deliberately created an advocacy coalition through careful and sustained engagement with OLAN and EPSAN around key topic areas.**

Sabatier and Jenkins-Smith (1993): Advocacy Coalition Framework (ACF)

While deep core beliefs remain stable, and are difficult to change, people's policy preferences can shift when they see compelling evidence or

experience major events. Learning within these coalitions is key to policy evolution. For example, a major disaster or breakthrough in science might cause coalitions to reconsider their policy positions. **Informed by this, we built structured opportunities and embedded strategic touch points—like Academies and Deep Dives—to allow for learning and change to happen.**

Shanahan, Jones, McBeth and Radaelli (2018): The Narrative Policy Framework (NPF)

Narrative strategies are used in an attempt to influence the policy process. The NPF identifies operational measures of policy beliefs through narrative elements such as characters and other symbolic, metaphorical, or contextual means by which collective understandings of the policy are generated. **The NPF informed the S3OK strategy of identifying and characterizing the policy narratives that shape responses to policy options, with an eye toward facilitating technical solutions to wicked problems.**

Jenkins-Smith and Weible (2025): Expanded and Updated ACF

In more complex policy arenas, outside influences like media, legislation, public opinion, and powerful stakeholders can influence what coalitions seek to accomplish. Moreover, trust and relationships among coalition members play a big role in how they learn and adapt. Accounting for this, we embedded input from public opinion via the M-SISNet and kept tabs on evolving state and national policy shifts. **This approach ensured S3OK research remained relevant and responsive to ongoing events,** and allowed us to carefully integrate conversations on key changes in policy and legislation during Academies, Deep Dives, and Working Group meetings when appropriate.

Methods for Collecting Data

The S3OK project implemented a comprehensive methodology to ensure the development of socially sustainable solutions. Data collection was key to this approach, combining surveys, focus group style deep dive discussions, engagement,

and feedback loops to define and evaluate solutions aligned with stakeholder values and priorities. This methodology ensured that the proposed solutions were not only technically feasible but also socially sustainable and widely supported.

To ensure broad based representation across the project's science focus areas, researchers designed and utilized a recruitment matrix for the OLAN. OLAN members were recruited across sectors and according to their expertise as it aligned with the primary research domains of the project. The team identified six sectors of interest for recruitment: public/elected official, public appointee, public-civil service, nonprofit, private industry/business, and other/miscellaneous. Crosswalked in the matrix with these 6 identified sectors were 4 domains of expertise: water, land management and agriculture, infrastructure, and a generalist category. Overall, this matrix ensured that the OLAN was comprised of members representing as many sectors and expertise categories as possible. Of note, there were instances where an individual had expertise across more than one category, thus totals in the matrix exceed the number of OLAN members. At full recruitment, representative statistics for OLAN members appear in **Table 3.1**.

These data collection points also allowed us to develop a robust understanding of diverse stakeholder conceptualization of problem areas and to track how beliefs, preferences, and problem definitions evolved over time. Combined, results from this data provided insights into shifting societal priorities and challenges that were used as inputs in the advancement of policy-informed scientific solutions to S3OK challenges.

Three primary data collection methods were used:

- Public opinion panel survey data (M-SISNet)
- Focus group-style Deep Dive discussions
- Engagement between the OLAN and EPSAN

Surveys and focus group style deep dive discussions provided stakeholder input. S3OK researchers relied on public opinion data from [The Oklahoma Meso-Scale Integrated Socio-Geographic Network \(M-SISNet\)](#) panel survey to

Table 3.1 OLAN Area of Expertise and Sector

Area of Expertise	Sector Represented					
	Public Elected Official	Public Appointee	Public Civil Service	Nonprofit	Private Business or Industry	Other
Water	1	0	16	4	8	4
Land Management/ Agriculture	0	2	5	2	3	4
Infrastructure	1	0	7	3	8	4
Generalist	2	1	4	3	4	2

gather insights on perceptions of key problem areas, feasibility of solutions, and willingness to support proposed solutions. The M-SISNet is a panel survey of about 1,500 households across Oklahoma that began in 2014. Participants were initially recruited through a random sample of residential addresses across the state. In 2021, with the launch of the S3OK project, a targeted group of new participants was added to help maintain the sample's demographic and geographic representativeness. During the S3OK project, panelists were contacted twice a year to complete in-depth surveys that captured their perceptions, experiences, and opinions related to the complex challenges addressed by the project teams.

We collected data through opinion surveys, focus group style discussions, and input from Oklahoma's leaders and households.

Through surveys of the public and focus group-style deep dive discussions with OLAN and EPSAN, we assessed key dimensions of solution development and refinement. These methods accounted for the diverse value orientations of Oklahoma stakeholders and ensured the proposed solutions would reflect a range of interests, be broadly acceptable, and reflect current cutting-edge advances in the science. Each year's insights shaped the direction of the next year's research and engagement efforts.

For example:

- The bi-annual M-SISNet public opinion survey provided a pulse on changing social beliefs and preferences, which informed the design of focus group discussions.
- Year three focus group style deep dive discussions revealed nuanced problem definitions and solution opportunities that guided policy discussions.
- OLAN-EPSAN interactions fostered new collaborations and connections among elite stakeholders and scientists, equipping decision-makers with up-to-date scientific advances directly relevant to their fields.

This process not only deepened the understanding of complex sustainability challenges but also allowed elite stakeholder groups in Oklahoma to move forward in their

respective fields with critical insights. These insights often spurred new interdisciplinary collaborations and generated actionable pathways for integrating cutting-edge scientific developments into real-world applications. The results of these actionable pathways are most evident in the potential for agreement and refining solutions, described in brief in the next section and in detail in subsequent chapters.

Potential for Agreement and Refining Solutions

As the project matured, insights gathered through extensive engagement and interdisciplinary collaboration helped shape a clearer set of core focus areas. In the process of advancing S3OK goals and objectives, and heavily informed by discussions at the Year three Academy, we identified three areas of agreement through a series of collaborative sessions involving both OLAN and EPSAN stakeholders. These areas of agreement culminated in the formation of three topically oriented working groups, composed of a cross-section of OLAN, EPSAN, and S3OK researchers covering:

1. Produced water reuse potential for oilfield and agricultural applications
2. Novel hybrid treatment and reuse options for stormwater and municipal wastewater
3. Natural hazards and utility resilience

Produced Water Reuse Potential for Oilfield and Agricultural Applications

This working group was designed to facilitate and enhance collaborations between researchers working to develop novel techniques to clean and pre-treat produced water for possible reuse, and stakeholders seeking solutions to challenges regarding water availability and water management, including logistical and financial challenges surrounding water access and/or disposal (**Figure 3.3**). This group's collectively defined goal was to make demonstrable progress towards the implementation of a small-scale pilot treatment opportunity for produced water

reuse and lay the groundwork for a five-year time horizon implementation guide that underscores future regulatory considerations.

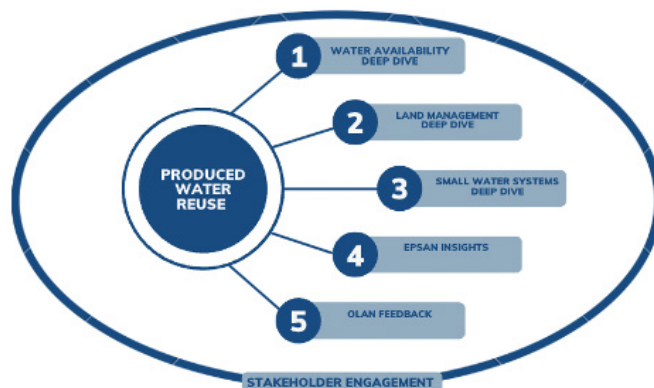


Figure 3.3. The Produced Water Group researches novel techniques to clean and pre-treat produced water for possible reuse.

Novel Hybrid Treatment and Reuse Options for Stormwater and Municipal Wastewater

This working group was designed to facilitate and enhance collaborations between researchers working to develop natural, active, and hybrid water treatment options and practitioners and stakeholders seeking solutions to challenges regarding water supply and management in the face of variable discharge quality and quantity (**Figure 3.4**).



Figure 3.4. The Novel Hybrid Treatment and Reuse Options for Stormwater and Municipal Wastewater Group develops natural, active, and hybrid water treatment options.

Natural Hazards and Utility Resilience

This working group is designed to facilitate and enhance collaborations between stakeholders tasked with maintaining and augmenting the physical resiliency of the electrical grid and researchers developing novel datasets and predictive techniques that can help stakeholders mitigate against new and increasing threats to resilience from changing extreme weather/climate conditions (**Figure 3.5**).



Figure 3.5. The Natural Hazards and Utility Resilience Group focused on the physical resiliency of the electrical grid.

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CHAPTER 4

Project Engagement, Structure, and Process



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46	Initial Engagement and Ongoing Cross-Sector Collaboration
47	Examples of Emergent Collaborations
47	D&B Oilfield Services
47	The Oklahoma Electric Cooperative and the Oklahoma Association of Electric Cooperatives
47	Oklahoma Water Reuse Action Plan and the Oklahoma Comprehensive Water Plan
47	Cross-Sector Communication
48	Project Structure
48	Extended Peer Science Advisory Network (EPSAN)
48	Opinion Leader Advisory Network (OLAN)
49	Oklahoma Meso-Scale Integrated Socio-Geographic Network (M-SISNet)
50	Student Leadership and Professional Development
51	Project Process
52	Engagement Process
52	Annual Research Retreats
52	State Conferences
53	Academies
54	Year Three Deep Dives
55	Working Groups
56	Solution Sets
56	Addressing the Impacts of Land Management Practices and Changing Weather Conditions on Water Availability for Agricultural Use/Land Management (ILM)
56	Evaluating Water Availability and Quality Under Changing Weather and Climate Conditions, with a Municipal Focus (WAQ)
56	Investigating Electric Infrastructure Impacts Resulting from Changing Land Cover, Weather, and Climate Conditions (EII)
60	Solutions Refinement Process
61	Working Group Solution Refinement
62	References

CHAPTER 4

Project Engagement, Structure, and Process

This chapter details the strategies for project engagement, overall project structure, and iterative processes developed to operationalize project vision and ensure that S3OK research remains both rigorous and relevant. Together, these elements illustrate how the S3OK project bridges research and practice.

This chapter will address:

- Initial engagement and ongoing cross-sector collaboration
- Project structure
- Project process

Initial Engagement and Ongoing Cross-Sector Collaboration

The project began with targeted initial engagement activities that explicitly brought together stakeholders from diverse sectors to focus on the specific goals of the project. These early interactions set the stage for deeper collaboration and created a platform for mutual learning across disciplines. As the

project progressed, additional cross-sector collaborations emerged, expanding beyond the initial framework. These collaborations were often driven by shared interests and the recognition that complex problems require multifaceted solutions. The following sections will address examples of emergent collaborations and explain cross-sector communication.

Examples of Emergent Collaborations

Through continued cross-sector engagement and collaborations, S3OK scientists were able to identify the kinds of analyses that were most needed and useful in a practical domain while advancing key elements of the science proposed. These partnerships not only shaped the direction of scientific research over the course of the project but also empowered stakeholders to address critical issues within their domains, demonstrating the reciprocal nature of the project. While building these collaborations required significant time, effort, and alignment of interests, the resulting synergy and shared commitment are essential for tackling complex, “wicked” problems and advancing sustainable, impactful outcomes.

We partnered with existing Oklahoma organizations, such as utilities and water management groups, to help identify areas of need and work together towards solutions.

Examples of these emergent collaborations include:

- D&B Oilfield Services
- The Oklahoma Electric Cooperative and the Oklahoma Association of Electric Cooperatives
- Oklahoma Water Reuse Action Plan and the Oklahoma Comprehensive Water Plan

D&B Oilfield Services

D&B Oilfield Services partnered with S3OK researchers and was an invaluable private industry partner to the project, significantly advancing the development of an economically viable and scalable treatment train for produced water. In Oklahoma, the oil and gas industry operations generate billions of gallons of produced water annually, creating both a challenge and an opportunity for water reuse. D&B Oilfield Services provided critical feedback to S3OK researchers to help address this issue, supplied produced water samples for testing, and hosted a working group meeting with a tour of their facilities, offering firsthand insights into full-scale wastewater treatment and re-injection processes. Their guidance highlighted resource extraction opportunities, such as iodine recovery and non-potable agricultural uses like cultivating Bermuda grass for state highway landscaping, Oklahoma's largest consumer of the crop. This collaboration underscores the importance of cross-sector partnerships in driving innovative, practical solutions that balance environmental and economic goals.

The Oklahoma Electric Cooperative and the Oklahoma Association of Electric Cooperatives

S3OK researchers partnered with the Oklahoma Electric Cooperative (OEC) and the Oklahoma Association of Electric Cooperatives (OAEC) to establish a data-sharing agreement that enabled detailed analysis of the electric grid's performance during the October 2020 ice storm. Using fine-grained outage data, the study revealed critical vulnerabilities in traditional radial distribution systems and identified specific failure modes caused by icing and tree limb interference,

providing actionable insights for OEC's resilience planning. This collaboration, rare due to the typical reluctance of utilities to share detailed data, fostered trust and innovation, allowing OEC to improve grid resilience while enabling S3OK scientists to develop a framework for analyzing interdependent infrastructure systems facing multiple hazards.

Oklahoma Water Reuse Action Plan and the Oklahoma Comprehensive Water Plan

The Oklahoma Water Reuse Action Plan (OWRAP) exemplifies cross-sector collaboration between OLAN and EPSAN, with S3OK researchers playing a leading role in developing key components of the plan. In particular, S3OK researchers supported OWRAP in survey design, data analysis, stakeholder engagement, and technical advancements. By integrating S3OK researchers into the development of OWRAP and the broader Oklahoma Comprehensive Water Plan (OCWP), the collaboration aimed to create actionable solutions for water reuse challenges while providing a sustainable framework for implementation. This process also helped inform and refine S3OK research, incorporating diverse perspectives and interdisciplinary expertise into ongoing scientific activities, including soil and agricultural sciences, to ensure impactful and symbiotic outcomes.

Cross-Sector Communication

It can be challenging to maintain effective communication across stakeholders with different backgrounds, schedules, and capacities. In response to these challenges, S3OK designed communication and collaboration processes to support successful communication. Successful communication depends on adapting processes to meet changing needs and avoid overwhelming stakeholders with irrelevant information. It is also important to leverage multiple channels of communication, like Slack, email, and in-person engagement.

Revisiting and revising communication processes over time as stakeholders expanded and new information became available was essential. For

We continuously refined our communication methods to improve stakeholder understanding and engagement.

example, S3OK used a “soft launch” approach to share updates and event invitations, allowing stakeholders to stay informed at a surface level without receiving excessive details.

Tailoring materials, such as offering concise fact sheets instead of full reports, and adjusting strategies based on the audience, improved communication and transparency. Established networks like EPSAN were leveraged to deliver targeted, less frequent updates, while embedded communication in meetings and verbal presentations helped engage stakeholders effectively. Continuous development and refining of communication processes, aligning strategies with stakeholder needs, and fostering informal channels have been central to S3OK’s success, building trust and support to achieve shared goals.

Project Structure

The S3OK project was structured around three primary stakeholder groups that remained engaged with one another throughout the project. These included the:

- Extended Peer Science Advisory Network (EPSAN)
- Opinion Leader Advisory Network (OLAN)
- Oklahoma Meso-Scale Integrated Socio-Geographic Network (M-SISNet)

These groups were composed of leaders from different sectors, scientists from several Oklahoma universities, and a representative

sample from the public. EPSAN and OLAN interacted throughout the duration of the project and formed the core structure of the S3OK project in the effort to identify acceptable solutions for a diverse group of stakeholders and Oklahoma residents.

Extended Peer Science Advisory Network (EPSAN)

The Extended Peer Advisory Network panel consisted of approximately 100 scientists from several institutions across the state of Oklahoma. This included an “internal peer network” of project team members, including science-focus team area members, postdoctoral researchers, and graduate students. The internal network was complemented by “external peer network” scientists, leading experts in their fields who focused on Oklahoma and had a unique ability to advise the project. These individuals held academic positions, but their work strongly aligned with practice and policy, thereby bridging an important gap between the science efforts and policy priorities.

Members of the EPSAN were invited to attend the annual Academy meeting, where they interacted with other scientists across different focus areas and with OLAN members to help identify and build sustainable solutions. Combined, the EPSAN and OLAN created a holistic panel of experts uniquely positioned to tackle Oklahoma’s “wicked” problems.

Opinion Leader Advisory Network (OLAN)

The S3OK Opinion Leader Advisory Network (OLAN) played a vital role in the EPSCoR project, serving as a practitioner advisory group of leaders from Oklahoma’s public, private, and nonprofit sectors (**Figure 4.1**). This network of opinion and thought leaders provided critical insights into how Oklahoma leaders perceived and responded to the state’s complex, “wicked” problems. OLAN members offered constructive feedback—sometimes challenging researchers—on the direction and impact of S3OK research while helping integrate science and policy into

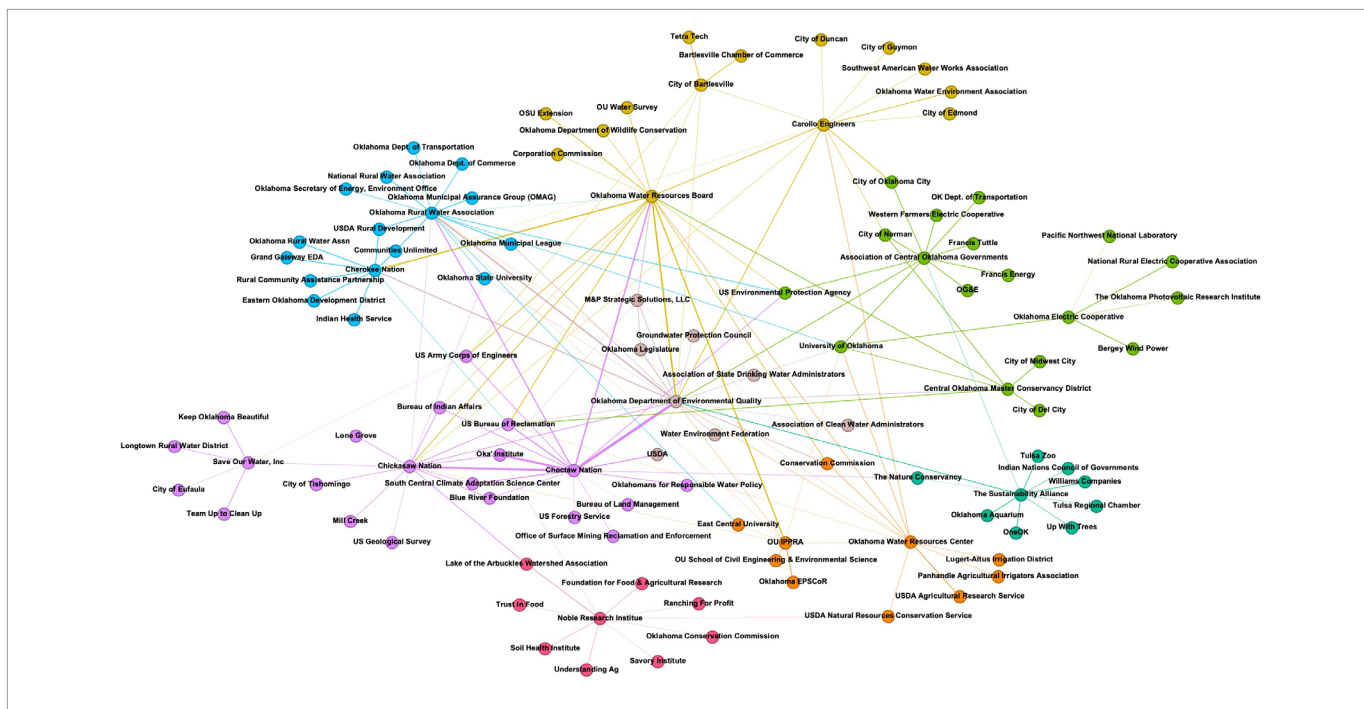


Figure 4.1. Map of the networks of collaborative relationships of OLAN-member organizations

strategic solutions for Oklahoma. Over time, they have advocated for implementing S3OK strategies and solutions in their respective fields. Conversely, OLAN members provided access to crucial data streams and resources that enabled S3OK research to advance in ways that would not have been possible without their support.

The OLAN was composed of over 70 individuals representing organizations across public, private, nonprofit, municipal, governmental, and tribal sectors. Recruitment was initially led by a community leader with over 30 years of experience in Oklahoma policy and politics, later augmented and continued by a key research practitioner with deep expertise in public and nonprofit collaboration. Particular effort was made to include a diverse array of groups, such as representatives from Tribal Nations and rural communities, to ensure diverse perspectives and equitable representation. The result was a dynamic advisory network that brought together individuals with varying experiences, interests, and organizational resources to collaboratively address Oklahoma's pressing challenges at the intersection of infrastructure, land use, and changing weather.

Oklahoma Meso-Scale Integrated Socio-Geographic Network (M-SISNet)

The Oklahoma Meso-Scale Integrated Socio-Geographic Network (M-SISNet) is a cornerstone panel survey designed to collect valuable insights from a network of up to 2,500 Oklahoma households. Since its initial deployment in 2014, M-SISNet has provided essential data to support EPSCoR research initiatives¹. The survey utilized an address-based random sampling approach, stratified by region, to ensure comprehensive geographic representation across both rural and urban areas of Oklahoma.

Administered biannually as part of the S3OK project since 2021, each iteration, or wave, of the survey sent to Oklahoma households was conducted online. The surveys collected data on public perceptions of weather, climate change, household resource use (e.g., water and energy), and other pressing topics. Core questions, such as those related to water, land use, and infrastructure, were repeated annually, while each wave also featured unique, thematic questions aligned with the science focus areas of the S3OK project.

The M-SISNet provided valuable insight from the public that informed ongoing S3OK research and was used to complement insights derived from other data components of the project. After the initial, wave 1 baseline survey, subsequent surveys included targeted sets of questions, or batteries, that addressed timely issues. To date, these have included topics related to S3OK such as modernization of the electrical grid, water reuse, and S2S weather products—among others. Each targeted set of questions offered actionable insights into public attitudes and willingness to support solutions, such as public willingness to pay for infrastructure improvements. These targeted question sets were constructed with insight from the science focus team areas and included:

- Wave 2: Modernization of the electrical grid
- Wave 3: Water re-use
- Wave 4: Eastern Red Cedar encroachment
- Wave 5: S2S weather products
- Wave 6: Infrastructure (energy and transportation infrastructure)
- Wave 7: Wildfire, water re-use, and produced water
- Wave 8: Water re-use

Data from each survey wave were made publicly available and shared with other science teams and the OLAN to ensure that research aligns with public priorities and stakeholder needs. Each wave of the survey was designed to reflect the ongoing research efforts, policy dynamics, and focusing events (like the [2021 cold air outbreak](#)), as well as conversations across stakeholder groups. The M-SISNet provided input from the public that helped identify stakeholder perspectives on the causes and impacts of complex challenges, as well as acceptable pathways for resolution. This process ensured that survey data continually shaped project outcomes, aligning research and policy recommendations with the needs and values of Oklahoma citizens.

Student Leadership and Professional Development

A critical element of the S3OK initiative was the recognition of student researchers as key stakeholders, underscoring their essential role in driving and sustaining the project's objectives. Students were not merely participants but active contributors whose work formed a vital part of the project's outcomes. By engaging in hands-on research, students gained a deep understanding of the complexities associated with "wicked problems" in Oklahoma and developed the skills necessary to address them. They collaborated within interdisciplinary teams, bridging diverse fields of expertise to tackle challenges at the intersections of science, policy, and community engagement. Their contributions led to numerous peer-reviewed publications, presentations at National Science Foundation (NSF) site visits and EPSCoR events, and appearances at discipline-specific conferences and workshops, showcasing their work on local, regional, and national platforms (**Figure 4.2**).

These opportunities not only advanced students' technical expertise and research capabilities but also trained them in interdisciplinary collaboration. This skill is increasingly critical for addressing complex societal issues that demand holistic, multifaceted solutions. Through their work on the project, students learned to integrate diverse perspectives, navigate institutional differences, and translate scientific findings into actionable recommendations for stakeholders.

Central to this initiative was the creation of a student-led, project-wide professional development group, supported by the Executive Board (EBoard). This group served as a cornerstone of the project's commitment to fostering the next generation of leaders. Students took ownership of their professional development by advocating for platforms to present their work, including oral and poster presentations, ensuring their research was visible and impactful. The group also spearheaded initiatives to create networking opportunities, allowing students to connect with peers across institutions and disciplines.



Student participation was a critical element of the project.

Figure 4.2. Student poster presentations at OK EPSCoR's Research Day at the Capitol.

These efforts were complemented by EBoard-supported, student-designed professional development events tailored to meet the unique needs and challenges of the student researchers. Faculty mentors provided guidance to ensure these events offered meaningful and relevant support, equipping students with the tools to succeed in their academic and professional careers.

The project's approach to student engagement extended beyond technical training to include leadership development. Students were empowered to assume leadership roles, organize events, and advocate for their own professional growth, reinforcing their confidence and capacity to influence the direction of interdisciplinary research. These experiences prepared students not only to excel in their current academic pursuits but also to become champions of interdisciplinary collaboration in their future careers.

In addition to advancing their individual growth, students contributed to the sustainability of the S3OK project by becoming part of a broader professional network that bridges academia and practice. By fostering meaningful connections with other researchers, policymakers, and community leaders, students played an integral role in translating project findings into actionable

strategies for addressing Oklahoma's wicked problems. Their efforts created a foundation for continued interdisciplinary engagement and ensured that the lessons learned from the project would be carried forward into future initiatives.

These investments in student researchers have created a legacy of leadership, with emerging professionals who are equipped to advocate for evidence-based solutions, interdisciplinary approaches, and community-engaged science. Through their contributions to S3OK, students have become integral to the project's success, forming a network of champions committed to advancing innovative, sustainable solutions to pressing societal challenges. This legacy ensures that the project's impact will endure as these leaders carry forward its principles and approaches in their careers across academia, policy, and practice.

Project Process

In addition to carefully curating a project structure to optimize the ability to meet project objectives, the S3OK project relied on a foundation of iterative engagement processes that facilitated the development of solution sets through select

touchpoints throughout the project's 5-year period. In this section, we outline:

- The engagement process
- Solution sets
- Solutions refinement process
- Working Group solutions refinement

Engagement Process

The S3OK engagement process was built around a dynamic, multifaceted approach that offered recurring opportunities for meaningful collaboration between project stakeholders. Initially centered on a three-pillar programmatic structure — Research Retreats, State Conferences, and Academies — this engagement process facilitated regular in-person interactions and fostered coordination and collaboration throughout the project.

In response to evolving stakeholder needs and emerging collective interests, the engagement process expanded in Years 3 through 5 to include topically oriented collaborative engagements. This evolution introduced focus-group-style Deep Dive discussions and Working Groups, which allowed concentrated stakeholder groups to explore specific cross-cutting themes in greater depth. These additions enhanced the project's capacity to address complex challenges and encouraged more focused, impactful collaborations.

By adapting to stakeholder input and evolving priorities while maintaining consistent communication, the S3OK Engagement Process exemplifies a responsive and inclusive approach, ensuring sustained engagement and meaningful outcomes for all involved.

Annual Research Retreats

As part of the initial three-pillar programmatic approach to engagement in the S3OK project, the S3OK Research Retreats were a cornerstone for fostering collaboration, advancing interdisciplinary research, and integrating education with research initiatives. Held each fall, these retreats were carefully designed to achieve multiple objectives:

1. **Collaboration and Knowledge Exchange:** The retreats provided a platform for researchers to share data, findings, and methodologies, facilitating the evolution of project goals and priorities. Student and early career researcher poster sessions and presentations highlighted ongoing work, while panel discussions and group engagements facilitated the exchange of ideas and the formation of new collaborations.
2. **Mentorship and Integration:** A key focus of the retreats was integrating students and postdoctoral researchers into the broader project team and providing structured mentorship for junior faculty. This approach ensured a talent pipeline and supported capacity building across career stages.
3. **Strategic Focus and Adaptation:** Each annual retreat emphasized a specific theme aligned with the project's evolving needs (**Figure 4.3**). Themes have included strengthening networks within the scientific community, addressing state-specific research priorities, and fostering partnerships between academia and industry. These targeted efforts ensure that the retreats remain responsive to emerging challenges and opportunities, maximizing their impact on the project's goals.

In addition to these objectives, the retreats were instrumental in promoting the integration of research and education, developing strategies to increase funding opportunities, and positioning the project for sustained success. Moreover, research retreats provided the S3OK researchers with an opportunity to iterate on the evolution of the projects' focus and scope based on what insights had been obtained in the year prior.

State Conferences

The second avenue for bolstering engagement in the S3OK project was the annual State Conferences. These annual conferences provided an essential and additional platform for sharing research progress, fostering collaboration, and engaging with a diverse network of stakeholders. Held each spring, these conferences were distinct from the fall Research Retreats, offering a broader public-facing venue to highlight S3OK's

achievements and connect with the broader research and stakeholder community.

The conferences featured keynote presentations by nationally recognized researchers, poster sessions, and targeted discussions that facilitated networking and the exchange of ideas among participants. Attendees included S3OK principal investigators (PIs), researchers, postdoctoral scholars, students, and stakeholders, ensuring a multidisciplinary and inclusive atmosphere.

Focused on themes central to the S3OK mission—weather, water, land management, and infrastructure—the conferences showcased progress and ongoing objectives, reinforcing the project’s relevance to state-specific challenges and national research priorities. Participants shared the most recent results from their research through scientific presentations and interactive poster sessions, offering opportunities for constructive feedback and collaboration.

These events also provided an avenue for NSF representatives and external evaluators to assess research outcomes and interact directly with the S3OK community, ensuring transparency and alignment with program goals. By bridging research and application, the State Conferences served as a dynamic space for engaging stakeholders, advancing project objectives, and strengthening the overall impact of the S3OK initiative.

Academies

A defining feature of the S3OK engagement structure, the S3OK Academies brought together S3OK researchers, EPSAN, and opinion leaders from the OLAN to connect and collaborate around tackling Oklahoma’s “wicked problems.” Held annually, these invitation-only events were aimed at providing a platform for researchers to share relevant findings from the year prior and collect data from participants that were used to guide the next iteration of research foci. This approach fostered interdisciplinary collaboration, advanced stakeholder engagement, and

facilitated the development of actionable solutions for complex societal challenges.

Each Academy provided a unique, additional platform for the OLAN and EPSAN to engage with one another. They were mindfully designed to enable open dialogue, iterative knowledge exchange, and sustained participant engagement. By integrating diverse perspectives, the Academies served as a critical nexus for aligning scientific research with public priorities and policy feasibility. Key objectives of the S3OK Academies were:

- **Facilitating Face-to-Face Engagement:** Academies created opportunities for EPSAN and OLAN stakeholders to meet in person, strengthening collaborations and fostering trust.
- **Guiding Collaborative Research:** Discussions centered on ongoing collaborative research progress, sharing insights from previous Academies, and exploring new directions for addressing wicked problems.
- **Developing Sustainable Solutions:** The Academies were instrumental in crafting solutions-oriented scientific workflows to address complex, interconnected issues in Oklahoma.

In addition to explaining and discussing the science central to these issues, the Academies provided the OLAN and EPSAN an opportunity to focus and guide the project in a way that facilitates informed policymaking. The OLAN provided feedback that guided the EPSAN’s efforts towards areas that had the most public salience or political feasibility. Over five years, this included:

- **2021 S3OK Academy:** Focused on the collective definition and prioritization of wicked problems. Participants engaged in roundtable discussions to identify areas of consensus and disagreement, establishing a foundation for future collaborative efforts.
- **2022 S3OK Academy:** Introduced Group Model Building (GMB) to refine problem definitions collaboratively. Pre-distributed

research summaries enabled attendees to maximize their networking and focus discussions on actionable goals. Engagement was further supported through Slack channels for ongoing collaboration and communication online to augment scheduled in-person programming. *For detailed analysis, see Olofsson et al. 2023².*

- **2023 S3OK Academy:** Achieved four key objectives, including disseminating concise updates on research progress, collecting data to refine solution sets, and strengthening connections within the S3OK network. This Academy deepened the iterative feedback process between OLAN and EPSAN members.
- **2024 S3OK Academy:** Marked a shift toward actionable solutions, debuting working groups to stakeholders. The Academy emphasized fostering lasting networks and preparing to implement research outcomes beyond the project's duration.
- **2025 S3OK Academy:** This capstone event focused on reviewing the project's achievements and facilitating discussions on future collaborations. It provided a comprehensive summary of S3OK's contributions and served as a launchpad for ongoing research and collaborations inspired by the initiative.

Through these annual Academies, S3OK combined diverse expertise to address Oklahoma's most pressing challenges. The events exemplified the project's commitment to fostering meaningful collaboration and advancing science-driven solutions with a lasting impact on policy and practice.

Year Three Deep Dives

Throughout the S3OK project and particularly at the May 2022 S3OK Academy meeting, OLAN and EPSAN members emphasized the need to develop cross-cutting understanding and approaches to S3OK advancements toward sustainable solutions to Oklahoma's wicked problems. This feedback led to the development of the Year Three S3OK Deep Dive discussion sessions, which were a strategic initiative to

address five critical cross-cutting challenge areas identified through collaborative discussions with S3OK researchers and OLAN. Each in-person, focus-group-style discussion session was held in strategic locations across the state. Each deep dive was aimed at developing integrated understandings and innovative approaches to tackle key environmental and infrastructural challenges in Oklahoma around five cross-cutting topic areas:

- **Implementing Land Management Strategies for Water Use Efficiency in the Context of Agricultural Systems:** Explored barriers and opportunities in implementing various land management strategies for water use efficiency, including red cedar management, soil health, and related plant and livestock management practices.
- **Unique Challenges for Small Water Systems:** Focused on the unique challenges small water systems in Oklahoma face, including infrastructure maintenance and implementation of new technologies, revenue/funding sources for small system projects, and workforce and training needs.
- **Stakeholder Engagement:** Explored existing Oklahoma stakeholder networks and strategies for enhancing current collaborations that address key environmental problem areas in Oklahoma.
- **Water Availability and Challenges in the Regulatory Environment:** Focused on challenges and opportunities posed by overlapping jurisdictions and competing interests in water-related outcomes in Oklahoma, with an eye toward how the regulatory environment influences the feasibility and timeframe for potential solutions.
- **Extreme Weather and Oklahoma Infrastructure Interactions (Wildfire Focus):** Focused on the interactions of wildfires and infrastructure systems in Oklahoma within the context of rapidly changing climatological trends and increased wildfire risk.

By curating focus-group-style discussions with relevant and interested stakeholders from across



Figure 4.3. Deep Dives provided the opportunity for more dedicated engagement around cross-cutting areas of interest.

sectors, the S3OK Deep Dives provided a single, standalone touchpoint for more dedicated engagement oriented around a range of cross-cutting areas of interest. These events marked a significant refinement and conceptual turning point for identifying pathways for potential solution refinement.

Working Groups

S3OK researchers established three topically oriented working groups focused on broader problem areas as a result of iterative analysis of findings from the S3OK Deep Dives and in response to feedback from OLAN and EPSAN members throughout the first three years of the project. These working groups reflected areas

of agreement and were designed to maximize synergistic efforts, broaden awareness of experimental successes and challenges, and provide a forum for discussing future funded collaborations. They also focused on aligning research directions with community and stakeholder needs and enhancing access to data and evidence-based outputs. The working groups target three key problem areas (**Figure 4.4**):

- **Novel Hybrid Treatment and Reuse Options for Stormwater and Municipal Wastewater:** Explored innovative approaches to treating and reusing stormwater and municipal wastewater, with a focus on sustainability and efficiency.
- **Produced Water Reuse Potential for Oilfield and Agricultural Applications:** Investigated opportunities for repurposing produced water to support oilfield and agricultural needs, aiming to reduce waste and enhance resource sustainability.
- **Natural Hazards & Utility Resilience:** Focused on addressing challenges associated with infrastructure resilience and disaster preparedness in the face of natural hazards, ensuring utility systems can withstand and adapt to increasing risks.

Working groups met at regular intervals, both at in-person and online working group meetings, across years four and five of the project. These working groups provided a dynamic platform for researchers and stakeholders to co-develop



Figure 4.4. Three areas were identified for advancing research.

solutions, refine collaborative approaches, and identify actionable steps for addressing Oklahoma's environmental and infrastructural challenges as the project came to a close. Through these efforts, the working groups laid the foundation for impactful post-S3OK collaborations. Working groups served to:

- Maximize opportunities for synergistic efforts
- Provide broader awareness of experimental successes and challenges
- Serve as a platform for discussing the potential for future funded collaborations
- Shape future directional steps toward implementation with community and stakeholder needs in mind
- Enhance access to existing data, data systems, and other evidence-based outputs
- Serve as a springboard for post-S3OK collaboration

Solution Sets

The S3OK engagement process set the stage for the iterative feedback to be provided by OLAN to S3OK scientists during the project's midpoint at the Year 3 Academy. Here, attendees were provided with an overview of key scientific solutions to S3OK challenges in three domains:

1. Addressing the Impacts of Land Management Practices and Changing Weather Conditions on Water Availability for Agricultural Use/Land Management (ILM)
2. Evaluating Water Availability and Quality Under Changing Weather and Climate Conditions, with a Municipal Focus (WAQ)
3. Investigating Electric Infrastructure Impacts Resulting from Changing Land Cover, Weather, and Climate Conditions (EII)

During the session, participants in each breakout room were presented with 8–10 preliminary components of potential solutions designed to address problems within S3OK challenge areas. Each of the solutions presented is either currently being researched or planned as an area for future inquiry. Science team representatives provided breakout room attendees with a broad

understanding of each solution component by presenting a brief, verbal overview of the research activities associated with each component.

Addressing the Impacts of Land Management Practices and Changing Weather Conditions on Water Availability for Agricultural Use/Land Management (ILM)

The ILM breakout room zeroed in on the challenges associated with land management and the dynamic weather and climate patterns affecting water availability for agricultural purposes. This breakout room served as a platform for the S3OK science team to present their progress on eight potential solution components for these challenges to the OLAN and ESPAN across the project (**Table 4.1**).

Evaluating Water Availability and Quality Under Changing Weather and Climate Conditions, with a Municipal Focus (WAQ)

Participants in the WAQ breakout room focused on 10 preliminary S3OK solution components aimed at addressing the impacts of changing weather and climate conditions on water availability and quantity, with a municipal focus (**Table 4.2**).

Investigating Electric Infrastructure Impacts Resulting from Changing Land Cover, Weather, and Climate Conditions (EII)

In this breakout room, participants reviewed nine prospective solution components designed to address two S3OK challenges associated with changing land cover and climate conditions' impact on electrical infrastructure (**Table 4.3**).

Table 4.1: S3OK Solutions Presentation to the ILM group at the Year 3 Academy

Addressing Impacts of Land Management Practices and Changing Weather Conditions on Water Availability for Agricultural Use	
S3OK Challenge Addressed	Potential Solution
Increasing Eastern Red Cedar encroachment, coupled with increasing frequency of drought/flash drought, leads to surface water depletion.	Quantify how restored native prairie improves water availability using ongoing monitoring; utilize these data to improve modeling and predictions.
	Understand and quantify social acceptance/public willingness to support Eastern Red Cedar, removal programs, particularly using controlled burns for smaller trees.
Reduced soil health due to land management practices and changing climate conditions, limiting water retention and rangeland resilience to drought.	Implement regenerative livestock grazing to improve soil water infiltration, as well as drought resiliency and soil health. EPSCoR supports research to compare two grazing management systems, adaptive and prescriptive, to determine the best method for improving soil health and overall sustainability.
Reduced water availability due to changing weather/climate conditions limits producers' ability to plan for optimal crop selection and maximize yields and creates a need for increased water efficiency and re-use.	Better meet long-term agricultural water needs and create the potential for year-round production by cleaning produced water using solar distillation to remove salinity and making it available for irrigation.
	Better meet long-term agricultural water needs and create the potential for year-round production by cleaning produced water using membrane distillation to remove salinity and making it.
	Identify instances and timing of extreme weather conditions, including flash drought, and improve future predictability of these events to assist producers in crop choice and irrigation planning.
	Utilize satellite data to monitor vegetation health and crop growth under varying water availability conditions in order to improve yield forecasting and support data-driven decision-making.
	Understand public risk perceptions and experiences related to water availability and related phenomena, such as drought, as an input into seeking water availability solutions that can receive public support.

Table 4.2: S3OK Solutions Presentation to the WAQ group at the Year 3 Academy

Water Availability and Quality Under Changing Weather and Climate Conditions: Municipal Focus	
S3OK Challenge Addressed	Potential Solution
Runoff from urban areas following pluvial events, coupled with inadequate water diversion infrastructure, results in contaminated water.	Improve predictions of frequency and severity of flash floods and pluvial events in order to better inform planners working to improve water diversion infrastructure.
	Identify/map flood-vulnerable locations and critical system components, and engage in spatial and temporal scale system monitoring to help prioritize stormwater system improvements and reduce cascading infrastructure failures.
Growing prevalence/requirements/ standards around removal of PFAS and other CECs.	Utilize wetland treatment units post-wastewater treatment and prior to water entry into another water body in order to reduce contaminant concentrations that are not addressed in traditional water treatment systems.
	Use chemical catalysts to destroy CECs in drinking water treatment systems with oxidation-based technologies.
	Understand public perceptions, acceptance, and trust of natural water treatment systems as opposed to engineered systems to assess feasibility.,
Risk of changing weather/climate conditions to reduce available water sources	Improve predictions of frequency and severity of flash and persistent drought in the short and medium term as an input into infrastructure planning, as entities seek to reduce water losses/reduce infrastructure inefficiencies.
	Understand public risk perceptions and experiences related to water availability and related phenomena, such as drought, as an input into seeking water availability solutions that can receive public support.
	Model potential reservoir management techniques are given for changing precipitation and temperature that may lead to increased water availability.
Public Hesitation Regarding Wastewater Re-use	Understand public willingness to accept wastewater under various re-use applications to assess the feasibility of projects.
	Design water treatment/re-use systems to minimize environmental impacts in construction, maintenance, and operations, thereby increasing the potential for public acceptance

Table 4.3: S3OK Solutions Presentation to the EII group at the Year 3 Academy

Water Availability and Quality Under Changing Weather and Climate Conditions: Municipal Focus	
S3OK Challenge Addressed	Potential Solution
Increasing Eastern Red Cedar, Encroachment, coupled with the increasing frequency of extreme weather (drought, heat, electrical storms, etc.) leads to increased wildfire risk.	Improve projections of future fire frequency and severity in the Southern Great Plains under changing weather/climate and fuel load conditions, in order to better inform decision-making and risk mitigation.
	Increase the predictability of the weather conditions that drive wildfire occurrence (including drought, electrical storms, heat), therefore increasing predictive ability for short and medium-term wildfire risks and aiding in decision-making.
	Assess economic impacts of the introduction of new ERC-based bioproducts industries (i.e., particleboard, mulch, and cedar oil) in Oklahoma through an integrated approach of spatial and economic impact analysis, in order to encourage mechanical removal and fire fuel load reduction.
	Understand and quantify social acceptance/public willingness to support Eastern Red Cedar, removal programs, particularly using controlled burns for smaller trees.
Need for increased physical resiliency of the electrical grid to mitigate the impacts of increasingly extreme weather/climate conditions.	Development of hazard maps that identify fire-vulnerable locations as they align with critical system components, and engage in spatial and temporal scale system monitoring to help prioritize system hardening, such as fire retardant for poles
	Model fragility of electric system components to extreme Conditions, including heat, cold, fire, and smoke, in order to prioritize system-hardening strategies
	Create network models of transmission and distribution systems to better understand cascading effects after failures and provide informational inputs into prioritization of mitigation strategies such as automatic switching/rerouting measures
	Increase predictability of future frequency and severity of extreme weather that threatens the grid, including cold snaps and heat waves
	Understand public risk perceptions and experiences related to extreme weather and electric outages, and measure public willingness to pay for system improvements so as to best understand which approaches may receive public support

Solutions Refinement Process

Refinement of S3OK Solutions was advanced using inputs from the Year 3 Academy Solutions Assessment Discussion and in the Working Groups. Following the presentation of each solution component discussed in the previous sections, open discussions allowed for feedback and clarifying questions prior to the quantitative evaluation of each solution component via scorecard (details below). Criteria for assessing solution components were iteratively developed through feedback from previous project meetings, focus-group style Deep Dive Conversations, and OLAN survey responses.

Ultimately, this process generated evaluation criteria for solution components that included the following dimensions:

- Urgency (1-low, 3-medium, 5-high)
- Effectiveness (1-low, 3-medium, 5-high)
- Social acceptability (1-low, 3-medium, 5-high)
- Technical Feasibility (1-low, 3-medium, 5-high)
- Cost (low, medium, high)

- Timeframe for Development/Implementation (Under 5 years, 5–10 years, 11+ years)

OLAN and EPSAN participants completed scorecards ranking each prospective solution component based on the criteria outlined above. Data from completed scorecards were de-identified, entered into a spreadsheet, and shared with breakout room participants at the end of the session.

After the Academy, information from the scorecards was used alongside transcripts from breakout room discussions as the basis for preliminary evaluation and analysis of prospective S3OK solutions. During analysis following the event, researchers created an overall ranking for each component by averaging the ranks across the four main dimensions. These summary rankings are shown in **Table 4.4** below. These three most highly rated solutions across each breakout room had common characteristics, in that all were rated as having a low (under 5 years) timeframe for development/implementation and were perceived to have a low or medium cost of implementation.

Table 4.4: Top Solution Components, by Average Ranking Across Dimensions

Breakout Room	Potential Solution	Rank*
ILM	Understand public risk perceptions and experiences related to water availability and related phenomena such as drought as an input into seeking water availability solutions that can receive public support.	4.08
ILM	Understand and quantify social acceptance/public willingness to support Eastern Red Cedar removal programs, particularly using controlled burns for smaller trees.	4.03
ILM	Quantify how restored native prairie improves water availability using ongoing monitoring; utilize these data to improve modeling and predictions.	3.87
EII	Understand public risk perceptions and experiences related to extreme weather and electric outages, and measure public willingness to pay for system improvements so as to best understand which approaches may receive public support.	3.96
EII	Understand and quantify social acceptance/public willingness to support Eastern Red Cedar removal programs, particularly using controlled burns for smaller trees.	3.93

Breakout Room	Potential Solution	Rank*
EII	Increase predictability of the weather conditions that drive wildfire occurrence (including drought, electrical storms, heat), therefore increasing predictive ability for short and medium-term wildfire risks and aiding in decision making.	3.85
WAQ	Understand public risk perceptions and experiences related to water availability and related phenomena, such as drought, as an input into seeking water availability solutions that can receive public support.	4.31
WAQ	Understand public willingness to accept wastewater under various re-use applications to assess feasibility of projects.	4.26
WAQ	Identify/map flood-vulnerable locations and critical system components, and engage in spatial and temporal scale system monitoring to help prioritize stormwater system improvements and reduce cascading infrastructure failures.	4.14

* Scores range from 1–Low to 5–High

In addition to considering the quantitative evaluation of potential solutions, the research team also analyzed transcripts from breakout room discussions, identifying key themes that informed the development of effective solutions. These included:

1. **Enhanced Technical Tools and Insights:**

Participants emphasized the need for improved forecasting models, particularly for flash droughts, and fine-grained, localized data to support short- and long-term planning in land management, infrastructure, and agriculture. Expedited access to accurate information was noted as a way to mitigate risks like wildfires and support adaptive strategies, even with trade-offs such as power quality adjustments.

2. **Integration of Economic, Legal, and Policy**

Considerations: Discussions highlighted the importance of incorporating regulatory and policy frameworks into technical solutions. Participants underscored the value of leveraging case studies and aligning with compliance needs, particularly in water management and infrastructure, to avoid redundant efforts and guide decision-making effectively.

3. **Scalable, Context-Appropriate Solutions:**

Participants called for tailored approaches to address region-specific challenges, such as outdated rural infrastructure and varying water availability. Updated resources like floodplain maps based on current conditions were identified as essential for effective planning.

4. **Public Awareness and Engagement:**

Effective communication and public input were deemed crucial, especially for water management. Participants stressed the importance of educating communities on water conservation, addressing fairness and costs, and using public surveys to guide solutions. Public opinion was recognized as a key factor in ensuring the successful implementation of initiatives.

These themes underscored the need for interdisciplinary, localized, and community-informed approaches to address environmental challenges in Oklahoma that were carried over into topically oriented Working Groups.

Working Group Solution Refinement

Drawing on the critical insights and lessons from the Year 3 Academy, working groups were

strategically organized around key challenge areas identified as priorities for advancing innovative solutions. Each group was tasked with translating complex challenges into actionable strategies, leveraging interdisciplinary collaboration to design, test, and refine solutions that addressed specific needs within their domains.

The working group development process emphasized an iterative and inclusive approach, bringing together diverse expertise from across disciplines and fields of practice. Through this collaborative effort, working groups developed impactful solutions that informed the creation of practical ‘products’—such as actionable insights, innovative technologies, or optimized processes. These products were carefully crafted to deliver measurable outcomes while aligning with S3OK’s overarching goals of sustainability, scalability, and real-world implementation.

The selection of solutions for refinement was driven by a dynamic combination of inputs, including:

- **Quantitative Evaluations:** Data-driven insights derived from rigorous analysis during the Year 3 Academy.
- **Collaborative Conversations:** Ongoing dialogue throughout the project to surface emerging needs and refine challenges.
- **Collective Effervescence:** The energetic exchange of ideas within the three problem area domains, fostering creativity and sparking actionable strategies.

By synthesizing these inputs, the working groups ensured that their solutions were not only technically robust but also context-appropriate and impactful, paving the way for meaningful advancements in the identified challenge areas of [Novel Hybrid Treatment and Reuse Options for Stormwater and Municipal Wastewater](#), [Produced Water Reuse Potential for Oilfield and Agricultural Applications](#), and [Natural Hazards and Utility Resilience](#) (**Figure 4.4**). Each of these working groups, and the corresponding challenge

areas they addressed, is discussed in detail in subsequent chapters.

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CHAPTER 5

Social and Scientific Challenges



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66	Responding to Evolving Environmental Risk Landscapes
67	Bridging Social and Scientific Divides
67	Bridging the Gap between Scientific Research and Societal Needs
67	Balancing Technical Solutions with Social Realities
68	Social Divisions and Conflicting Narratives
68	Honoring Multiple Perspectives
68	Legacy Ties and Local Context
69	Polarization and Conflicting Priorities
70	Scientific Challenges
70	Forecasting Limitations
70	Data Availability
71	Institutional and Disciplinary Silos
71	Identifying Domains of Agreement Despite Divides
72	Despite Cultural Divides
72	Despite Disciplinary Divides
72	Despite Fields of Practice/Professional Orientation
72	Domains of Agreement

CHAPTER 5

Social and Scientific Challenges

This chapter examines the complex social and scientific challenges that S3OK – a team of scientists, practitioners, and stakeholders – has faced in tackling wicked problems at the intersection of weather, water, land use, and infrastructure in Oklahoma. These challenges arise from shifting environmental risks, entrenched disciplinary boundaries, political polarization, and deep-seated cultural divides. Recognizing these barriers, S3OK has worked deliberately to bridge gaps between expertise areas, foster dialogue across sectors, and develop research-based materials to support decision-making and implementation.

By approaching these issues through an interdisciplinary and cross-sectoral lens, this section outlines how S3OK has navigated challenges while seeking common ground. Specifically, the following sections detail how S3OK has:

1. Responded to evolving environmental risk landscapes
2. Bridged social and scientific divides to enable collaboration
3. Identified domains of agreement despite ideological and disciplinary differences

Responding to Evolving Environmental Risk Landscapes

Oklahoma's environmental risks no longer sit still. Extreme heat, sudden downpours, and longer dry spells now collide with aging infrastructure, shifting land use, and rising water demands, creating a single, intertwined threat rather than

separate problems. As **Figure 5.1** illustrates, the old “average” weather on which planners once relied has lost its meaning. Managing today's risks, therefore, requires an adaptive, cross-sector playbook—one that treats climate and infrastructure stresses as moving targets and



Figure 5.1. Shifting weather patterns produce both drought and flooding, making resilience planning more difficult and upending long-held assumptions. *Photo Credit: Sean Ernst.*

updates strategies as conditions evolve.

At the core of this challenge is the interdependence of natural and built systems. Decisions about land use, whether related to Oklahoma's robust agricultural or energy development sectors or municipal planning, directly impact water availability and quality as well as infrastructure resilience. In turn, legacy water management systems, stormwater infrastructure, and well-established land-use policies struggle to accommodate the increasing variability in subseasonal-to-seasonal weather patterns. More frequent droughts, extreme precipitation events, and shifting groundwater

dynamics complicate long-term planning for municipal water supplies, agricultural irrigation, and flood control, leading to greater uncertainty in managing Oklahoma's essential resources.

These environmental shifts also bring social and political complexities. Competing demands for water, land, and infrastructure investments often reflect historical tensions and conflicting priorities between communities, industries, and governance. As a result, resilience strategies that fail to consider the broader social, economic, and political landscape risk deepening existing challenges rather than addressing them. The problem is not only scientific but also deeply tied to governance, policy, and public perception.

The S3OK project explored these intersections, leveraging scientific research, data-driven forecasting, and interdisciplinary collaboration to develop more integrated approaches and socially sustainable solutions to wicked problems. This chapter examines the emerging environmental risk landscape, the limitations of traditional methods in addressing it, and the scientific and social challenges that must be overcome. In doing so, it provides key context for advancing understanding of how to better align land, water, infrastructure, and climate resilience strategies in a world where environmental risk is constantly evolving.

Bridging Social and Scientific Divides

Navigating the wicked problems S3OK seeks to address presents a set of complex, interwoven challenges that span both social and scientific domains. While scientific advancements offer technical pathways to identify solutions to these challenges, the effectiveness and durability of these solutions depend on their alignment with social realities, community needs, and policy frameworks. The S3OK initiative recognizes that scientific expertise alone cannot drive meaningful change. Solutions must be co-developed with stakeholders, accounting for political feasibility, economic pressures, and public perceptions.

Bridging the Gap between Scientific Research and Societal Needs

One primary core challenge the S3OK project sought to address is the challenge of bridging the gap between scientific research and societal needs in the solution development process. While researchers work to develop better predictive models, adaptive water management strategies, and climate-informed land-use policies, these advancements can struggle to gain traction if they do not align with the priorities and needs of communities, industries, and decision-makers.

Moreover, if such advances are technically and practically inaccessible and siloed, the scale of potential influence is limited. For example, while data-driven approaches to water allocation may highlight the long-term benefits of conservation, immediate economic concerns—such as agricultural productivity or municipal water access—often take precedence in policy discussions.

Furthermore, if such innovative data-driven approaches to water allocation are circulated within scholarly networks or venues alone, key findings and insights might not make their way into the hands of practitioners in positions to benefit from their implementation. The challenge lies in integrating technical solutions into decision-making processes that are inherently shaped by political, economic, and social considerations.

Balancing Technical Solutions with Social Realities

Balancing technical solutions with social realities is particularly difficult in contexts where scientific recommendations conflict with economic interests or deeply held cultural beliefs. Infrastructure innovations designed to mitigate flooding or optimize water distribution, for example, may face resistance if they do not adequately consider factors related to land ownership and land use norms, agricultural practices, or urban planning regulations. Similarly, efforts to enhance forecasting capabilities for drought or extreme weather are only effective if policymakers, water

managers, and the public trust and use the information.

One of the greatest barriers to working across social and scientific challenges is effective risk communication. Different groups interpret scientific uncertainty, probabilistic models, and policy trade-offs in different ways. Scientific recommendations are often based on probabilistic outcomes, while decision-makers may seek clear-cut answers about when, where, and how a specific risk will materialize in order to make informed decisions. When forecasts or scientific assessments fail to provide certainty, or when different experts present conflicting views, public trust in science and institutions can erode.

In Oklahoma, where land and water use policies are shaped by varied and sometimes conflicting interests, the role of trust in institutions and expertise becomes a key determinant of whether resilience measures are adopted, contested, or ignored. Skepticism toward science, government regulation, and external expertise can create resistance to policies that can promote effective solutions to challenges related to water quality and quantity, land use, and mitigation practices. Conversely, local knowledge and historical experience, along with industry and practitioner priorities, often hold significant weight in shaping community-level decisions. Building long-term relationships with key stakeholders rather than engaging them only in moments of crisis can help ensure that scientific insights and decision-making priorities are well aligned to meet the new and established challenges. As S3OK researchers worked across disciplines and stakeholder groups, fostering trust and transparency in communication while developing meaningful professional relationships was essential.

Social Divisions and Conflicting Narratives

The challenges of working across social and scientific boundaries are further complicated by long-standing divisions and historical tensions in decision-making processes. The following section explores how cultural divides, legacy ties, and polarization shape public

perceptions of environmental risk. These tensions must be acknowledged and addressed if resilience planning efforts are to be effective and sustainable in the face of increasingly unpredictable environmental conditions.

Honoring Multiple Perspectives

Oklahoma's unique mix of urban and rural landscapes, along with strong regional and cultural differences, presents rich opportunities and unique challenges in developing socially sustainable solutions at the intersection of land use, water quality and quantity, and infrastructure in the face of changing seasonal to sub-seasonal weather patterns. Equipped with different resources and characterized by different needs, Oklahomans hold differing perspectives and priorities that can create tensions if advancing a 'one-size-fits-all' approach to solution development. Not only does such an approach lack credibility and applicability, but it also presents the challenge of inappropriately leveraging scientific expertise and developing policy recommendations that conflict with local observations. Overcoming this divide requires not just improving technical accuracy but also incorporating insights from across the full extent of Oklahoma's landscape while seeking to build trust and foster two-way communication between scientists and local stakeholders.

Legacy Ties and Local Context

Oklahoma's economic and historical engagement with the select sectors has created deep cultural and identity-based connections to traditional industries in the state. Communities, particularly those with economies built around such sectors, such as traditional energy production and agriculture, may view innovative strategies designed to adapt to a changing environment as threats to their economic stability (**Figure 5.2**). Resistance to change is not merely about skepticism toward new technologies; it is also about protecting livelihoods, maintaining local economies, and preserving a way of life.

This dynamic is evident in debates over energy security planning, policies focused on water

quality, quantity, or land use, and traditional climate adaptation strategies. Proposals to shift away from familiar measures to address challenges in these areas may face opposition from communities where resources available to support new initiatives are limited and where jobs in traditional industries are central to local identity and economic survival.



Figure 5.2. Oklahomans are deeply divided about changing technologies and traditions. *Photo Credit: Sean Ernst.*

Similarly, tensions arise when adaptation policies impact agricultural and ranching communities, which have long-standing relationships with land and water resource managers. Restrictions on water use, incentive structures, or changes to land management regulations may be viewed as unnecessary government intervention, even when designed with long-term improvements in mind. Without meaningful input from the public and the development of solutions that address both economic realities and environmental risks, adaptation strategies can be perceived as top-down impositions rather than collaborative efforts.

Polarization and Conflicting Priorities

In addition to challenges oriented around legacy, local context, and balancing multiple perspectives, conflicting priorities across stakeholder groups pose a challenge to the development of sustainable solutions to wicked problems. While stakeholders may acknowledge the wicked problems Oklahoma faces, their interpretations of risk and subsequent priorities may diverge based on economic, institutional, and social interests. These differences can create competition for resources, policy gridlock, and challenges in achieving long-term, coordinated resilience strategies.

One such example of this kind of conflict exists between agricultural, municipal, and industrial water users. Farmers and ranchers, for example, may prioritize consistent water access for irrigation and livestock, while municipalities focus on drinking water security and urban flood mitigation. Meanwhile, industrial stakeholders, including energy producers and manufacturers, often require large water allocations for production processes. As variability in subseasonal to seasonal weather threatens water availability, disputes over allocation rights and regulations can intensify, making it difficult to develop effective policies.

Professional silos further exacerbate these divides. Local, state, and federal agencies often have overlapping yet disconnected roles in managing water resources, land use regulations, and infrastructure funding. These agencies may operate under different mandates and priorities, leading to fragmented decision-making processes that make it difficult to coordinate large-scale resilience efforts. For instance, while one agency may push for drought contingency plans, another may prioritize short-term economic growth strategies that increase water demand, leading to policy misalignment.

Resolving these conflicts requires strategic engagement, cross-sector dialogue, and collaborative planning approaches. Rather than approach solving these wicked problems as

zero-sum competitions between stakeholders, the S3OK approach identified solutions that provide shared benefits that serve multiple interests while advancing solutions to wicked problems incrementally. By creating opportunities for consensus-building, the S3OK initiative aims to bridge institutional divides and stakeholder conflicts, ensuring that resilience strategies are both scientifically grounded and socially feasible. Of equal importance is that the process builds trust among stakeholders through successfully and jointly tackling tough problems, which makes addressing the next (perhaps even more challenging) problems less daunting.

Scientific Challenges

Developing socially sustainable solutions to wicked problems in Oklahoma requires both scientific advancements and social feasibility. While technical solutions offer new pathways for resilience, scientific limitations in forecasting, data access, and interdisciplinary collaboration create obstacles to implementation. Developing socially sustainable solutions demands not only improved models and datasets but also institutional coordination and knowledge-sharing across multiple stakeholder groups to increase trust and build problem-solving capacity.

Forecasting Limitations

Effective management of water resources, land use, and infrastructure resilience is driven, in part, by weather variability and the associated impacts. This is particularly acute in Oklahoma, where the unique geography and meteorological conditions present varied and hazardous weather dynamics on a seasonal basis.

On this point, one of the greatest scientific challenges lies in the predictability gap in [subseasonal-to-seasonal \(S2S\)](#) forecasting. Known as the “predictability desert,” this gap represents the difficulty in producing reliable weather and climate forecasts for the critical 10-to-90-day timeframe—a window that is too long for short-term weather models but too short for long-term climate projections. This limits the relevance of forecasting models in the short to

medium range timeframe for stakeholders, such as agricultural workers, water systems managers, and utility operators, to anticipate and respond to droughts, extreme precipitation events, and compounding hazards.

The gap between forecasting models and actionable decision-making timelines complicates resilience efforts, particularly given the gap between timescales in forecasting and local planning. While forecasting models at the subseasonal-to-seasonal scale can indicate near-term trends in temperature, precipitation, and hydrological conditions, they often lack the spatial and temporal precision needed for specific local applications. This limits their utility for short-term operational decisions, such as enacting temporary water use restrictions or preparing utility systems for infrastructure stress. In contrast, longer-term decisions, such as large-scale water purchases or land-use regulation, typically rely on multi-year climate outlooks and broader planning frameworks. Without clearly linking forecast products to relevant decision timelines, the potential for forecasting tools to support adaptive responses remains underrealized.

Compounding these challenges is the difficulty in predicting multi-event disruptions, where extreme conditions occur simultaneously or in succession. For example, an S2S forecast may indicate an upcoming heatwave, but how that heat wave interacts with prolonged drought, wildfire risk, or energy demand spikes remains highly uncertain. The inability to forecast these complex interactions undermines efforts to develop early warning systems and proactive mitigation strategies for infrastructure, agriculture, and water resource management.

Data Availability

The effectiveness of scientific modeling and resilience planning is further constrained by gaps in data availability and accessibility. In Oklahoma, where utilities, government agencies, and private industries all manage critical infrastructure and water resources, proprietary or classified datasets often limit researchers’ ability to develop comprehensive, real-time analyses and hinder

meaningful synergistic collaboration. Electric grid operations, water usage statistics, and land development records are frequently unavailable to researchers due to legal, regulatory, or competitive restrictions, making it difficult to create models that reflect real-world conditions.

Even when data are accessible, they are often fragmented and inconsistent across disciplines. Hydrologists, social scientists, climatologists, land-use planners, and engineers work with distinct datasets, methodologies, and analytical frameworks, creating barriers to interdisciplinary collaboration. For example, a watershed model developed by hydrologists may not align with the infrastructure planning models used by municipal agencies, leading to misaligned resilience strategies. Without standardized data-sharing agreements and mutual understanding, researchers, policymakers, and industry leaders struggle to create holistic, cross-sector solutions to resilience challenges.

Institutional and Disciplinary Silos

Beyond data constraints, institutional and disciplinary silos create further barriers to collaborative planning and solution development. Many efforts at solution development are sector-specific and implemented in a way that addresses challenges from a singular perspective. This results in impacted stakeholder groups operating independently of one another. This lack of integration makes it difficult to coordinate policies, share expertise, and implement cross-cutting solutions.

Disciplinary silos also impede knowledge exchange between social scientists, engineers, policymakers, and industry leaders. While technical experts develop models and infrastructure solutions, social scientists focus on risk perception, stakeholder engagement, and policy implementation. However, without direct collaboration, scientific advancements may fail to account for social realities, and policy efforts may not reflect technical feasibility. Bridging this gap requires structured mechanisms for interdisciplinary dialogue that ensure that

scientific research informs, and is informed by, societal needs.

Further complicating coordination are the overlapping yet disconnected responsibilities of federal, state, tribal, and local agencies. Water management, for example, is overseen by multiple agencies with different jurisdictions, leading to conflicting regulations and fragmented decision-making. This disconnect is particularly problematic when addressing multi-jurisdictional issues like groundwater depletion, flood control, and drought preparedness, where solutions require coordinated action across political and administrative boundaries.

Identifying Domains of Agreement Despite Divides

Identifying domains of agreement despite the challenges described above requires technical innovations that promote convergence solutions to wicked problems that cut across competing social narratives. S3OK researchers are uniquely positioned to lead these efforts through interdisciplinary science that advances cohesive solutions-oriented strategy despite cultural and disciplinary divides or fields of practice.

Despite Cultural Divides

Cultural orientations that shape perspectives on resource management and policy interventions often vary widely, particularly between urban and rural communities, and across stakeholder groups. To build consensus, efforts to develop socially sustainable solutions to wicked problems must:

- Identify and prioritize shared concerns rather than emphasizing politically divisive framing.
- Focus on risk management, making it clear that identifying solutions to wicked problems is about protecting livelihoods and critical resources, not advancing a political agenda.
- Emphasize collaboratively developed solutions that respect local values and priorities, ensuring that scientific solutions reflect the

needs, knowledge, and expertise of a region rather than imposing top-down policies.

Despite Disciplinary Divides

Addressing wicked problems in Oklahoma requires breaking down traditional academic and professional silos that separate social and physical sciences and keep practitioners, the public, and academics from developing synergistic relationships. S3OK seeks to erode these silos and foster collaboration by:

- Creating interdisciplinary research frameworks that integrate the full extent of scientific and scholarly expertise in the state across a broad network of institutional partners, ensuring a holistic approach to resilience.
- Encouraging the co-production of knowledge through cross-sector collaborations, so that scientific advancements are shaped by practical experience and community needs.
- Using innovative research methods to include local stakeholders in data collection, risk assessment, and policy development, ensuring that scientific analysis reflects on-the-ground realities.

Despite Fields of Practice/ Professional Orientation

Advancing socially sustainable solutions to wicked problems requires coordination across a wide range of professional groups, including utilities, policymakers, emergency managers, engineers, researchers, and the public. However, differing priorities, terminologies, and decision-making processes often hinder effective collaboration. To address this, S3OK promoted:

- Multi-stakeholder partnerships that brought together diverse expertise to design and implement integrated, actionable solutions.
- The development and maintenance of a shared language and common goals ensured that scientific data, policy frameworks, and engineering solutions were accessible and applicable across stakeholder groups.

- Ongoing dialogue and iterative learning processes, allowing for sustainable solutions to be refined over time based on new data, shifting environmental risks, and emerging social challenges.

Domains of Agreement

Despite key differences, careful efforts to identify core domains of agreement provided a foundation for the development of socially sustainable solutions. Identified domains included:

- Infrastructure reliability, energy security, and stability must remain a priority across government, industry, and communities.
- Data-driven decision-making is essential for enhancing preparedness and minimizing risk.
- Scientific solution generation must be adaptive to accommodate evolving risk landscapes associated with changing weather patterns, water availability, and land-use challenges while respecting the regulatory landscape and public priorities.
- Cost-effective solutions must balance economic, social, and environmental priorities to ensure long-term sustainability and stakeholder buy-in.

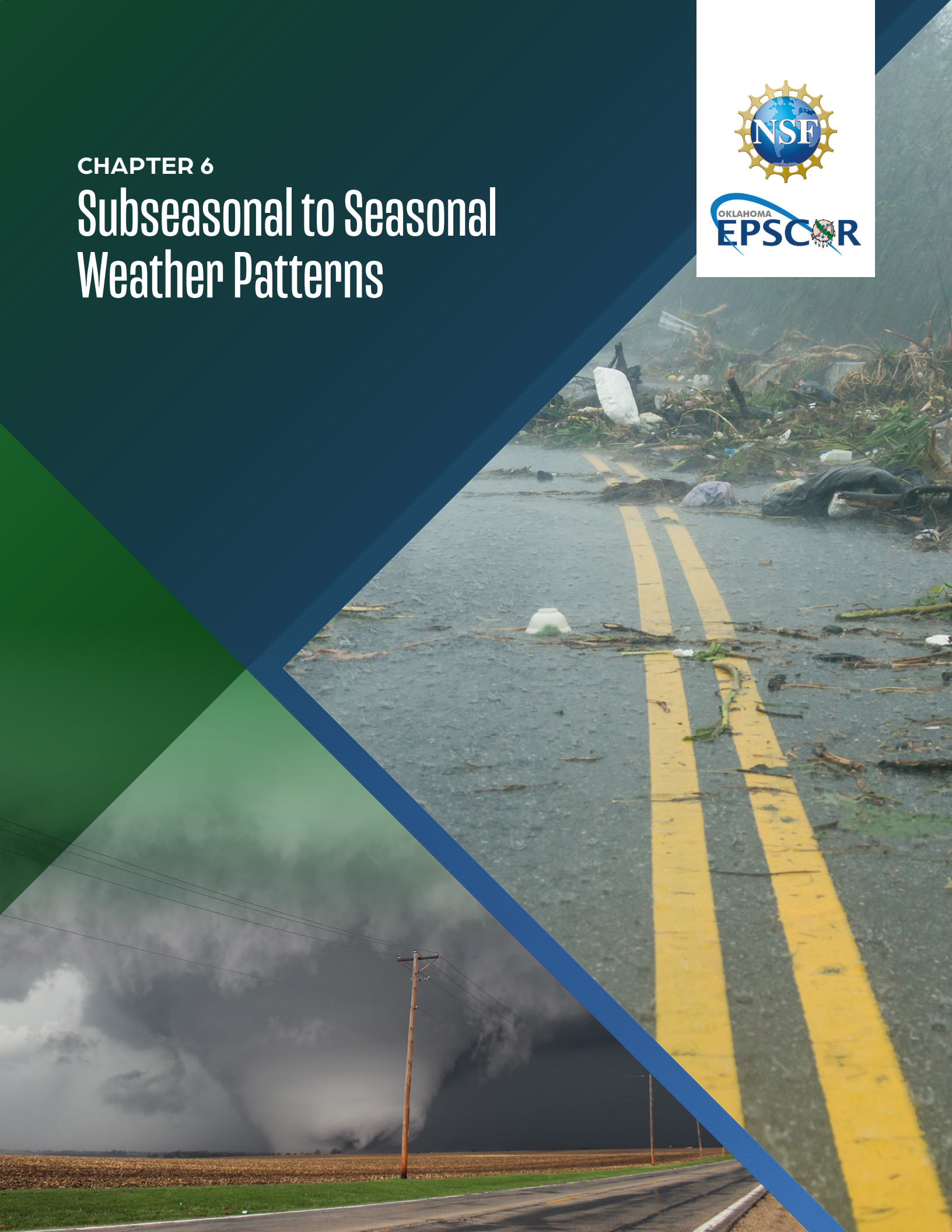
The S3OK approach bridged divides, integrated diverse expertise, and fostered collaboration to develop socially sustainable and scalable solutions for Oklahoma's wicked problems. Despite shifting risks and increasing uncertainty, researchers and stakeholders navigated cultural, economic, and political realities while making coordinated scientific, technical, and social advancements that can facilitate decision-making and policy adoption.

By focusing on shared priorities, S3OK helped create common ground among stakeholders who may otherwise have remained mired in conflicting perspectives. Through cross-sector dialogue and collaborative knowledge production, S3OK sought to ensure that science-informed solutions are not only effective but also have the potential for broad public acceptance and implementation. By breaking down institutional silos, addressing

conflicting narratives, and prioritizing long-term sustainability, S3OK helped build a future for Oklahoma that balances economic, social, and environmental priorities while ensuring a sustainable pathway forward.

CHAPTER 6

Subseasonal to Seasonal Weather Patterns



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77	What is Subseasonal to Seasonal (S2S) Weather?
79	What Drives S2S Weather Patterns?
81	Improving S2S Forecasting
81	Improving S2S Forecasting of Extreme Temperatures in Oklahoma
81	Heatwaves
82	Reexamining Heatwaves using Wet Bulb Globe Temperature
82	Examining the Emergence of Winter Heatwaves
82	Understanding and Improving S2S Forecasting of Heatwaves in Oklahoma
82	Cold Air Outbreaks and Temperature Whiplash
83	Identifying New Sources of Predictability of CAOs
83	Predicting Wintertime Temperature Whiplash Events
84	Implications for S2S Forecasting and Climate Resilience
84	Flash Droughts: Understanding Their Increasing Frequency and Predictability Challenges
84	Precipitation Whiplashes: Advancing S2S Forecasting of Precipitation Extremes in Oklahoma
85	Predicting Rapid Shifts Between Extremes: The Challenge of Precipitation Whiplash Events
86	Linking Precipitation Abnormalities to Wildfire Risk
86	Defining and Predicting Precipitation Whiplash Events at the S2S Timescale
86	Improving S2S Forecasting and Climate Adaptation
86	Social Dynamic Considerations of S2S
87	Assessing Public Understanding of S2S Forecasting for Extreme Events
87	Evaluating Public Perceptions and Socioeconomic Impacts of S2S Extreme Events
87	Bridging the Gap Between Perception and Reality
88	Understanding Awareness of Drought Through Digital Behavior
88	Assessing Implications for Policy and Risk Communication
88	References

CHAPTER 6

Subseasonal to Seasonal Weather Patterns

Oklahoma faces significant changes in its natural environment and human systems due to weather patterns over short periods—ranging from 10 to 90 days. Weather on this timescale, known as subseasonal to seasonal (S2S) weather, include rainfall and temperature patterns and sometimes more extreme events (e.g., heavy rainfall, heatwaves) that can be particularly costly and disruptive.

Diagnosing trends in S2S weather patterns are especially difficult to address because they are happening alongside debates about the role of human activity in driving climate change. These debates can make it harder for people to recognize and respond to the impacts of S2S weather. On the science side, the S2S timescale lies in a “predictability desert.” That is, the timeframe starts at the end of the more traditional “weather models” used for forecasting (out to 10 days) but ends short of seasonal (3–9 months) timescales, where signals from the ocean and land offer good prediction skill at those times. Indeed, S2S forecasting represents the “new frontier” in forecasting. To tackle these challenges, S3OK researchers focused on advancing research that facilitated:

- Better understanding of the basic processes driving S2S patterns
- Improving models and predictions of basic S2S phenomenon
- Developing S2S data for managing water, carbon/water cycles, and infrastructure in Oklahoma
- Better understanding of the social dynamic considerations of S2S

By improving S2S forecasting and integrating insights from public perceptions, researchers aimed to help community leaders and residents find practical and socially sustainable solutions to the growing risks from extreme weather events. This chapter provides a broad overview of S2S dynamics and critical context for work S3OK researchers advanced through the project. This includes:

1. What is Subseasonal to Seasonal (S2S) Weather
2. What Drives S2S Weather Patterns
3. Improving S2S Forecasting
4. Social Dynamic Considerations of S2S
5. How S2S Drives Wicked Problems and the S3OK Challenge Areas

What is Subseasonal to Seasonal (S2S) Weather?

Oklahoma is part of the Great Plains, a region stretching from southern Texas to North Dakota and eastern Montana. This area experiences some of the most dynamic and extreme weather in the country, including:

- **Severe thunderstorms** with high winds, large hail, and tornadoes
- **Winter storms** that bring heavy snow, ice, and exceptionally cold temperatures
- **Extended heatwaves** during summer

Adding to this complex and dynamic weather landscape, Oklahoma sits in a transition zone between the dry west and the wetter east. This unique position causes precipitation amounts to

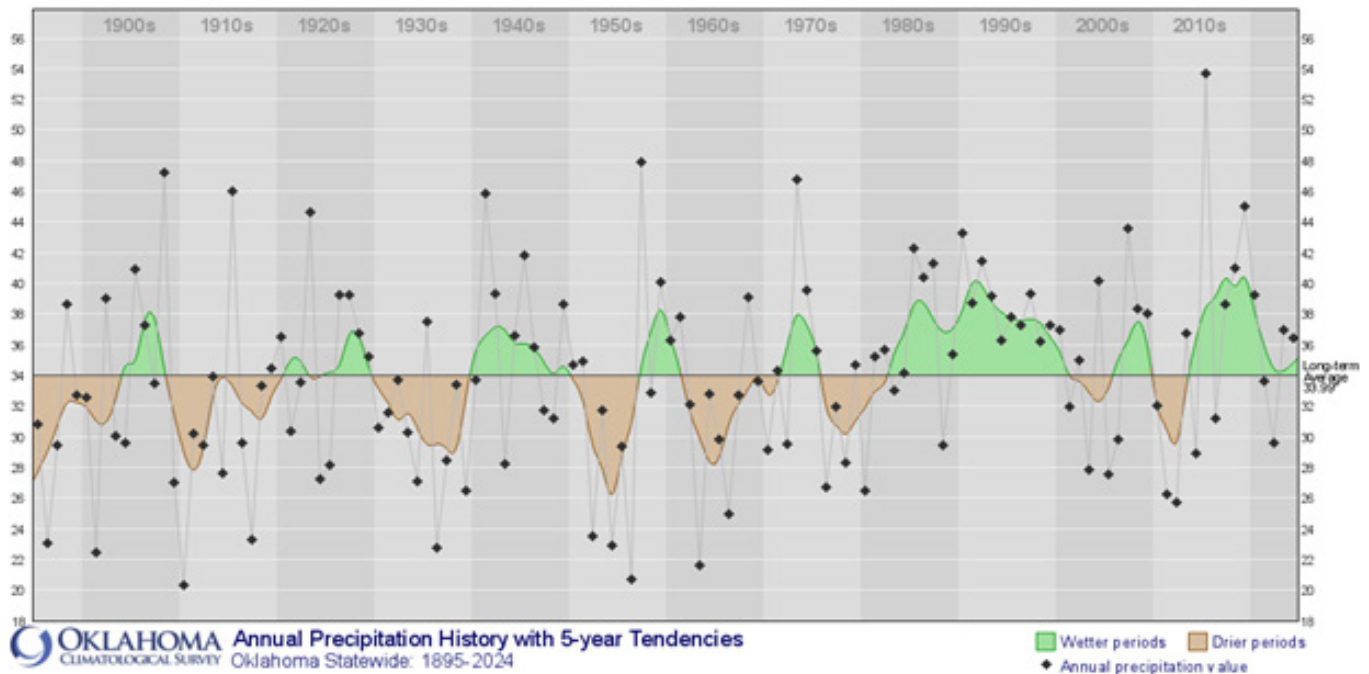


Figure 6.1. Statewide-average annual precipitation totals (inches) in Oklahoma from the late 1890s to 2024 (black line with diamonds) and the 5-year running mean value (thin brown/green line). Periods of time colored brown indicate drought periods, and periods of time in green indicate pluvial periods. *Courtesy of the Oklahoma Climatological Survey.*

vary greatly from year to year (**Figure 6.1**). As a result, the region sees large swings in weather and temperature over S2S timeframes, making it especially challenging to predict and manage weather impacts.

Advancements in meteorological observational networks, computational power, and physics-based numerical weather prediction models have steadily improved forecast accuracy for short- to medium-range forecasts, up to about 5–10 days¹ (Bauer et al., 2015). Today, the frontier for weather prediction is in the S2S time range. Beyond this window, forecasting enters what scientists call a “predictability desert”², characterized by major opportunities to improve forecasting accuracy.

Despite these challenges, improving S2S predictions is a top priority in meteorology because of their immense value across multiple sectors³. Affected sectors include:

- Public health⁴
- Renewable energy⁵
- Agriculture⁶
- Water resource management⁷

Many of these applications focus on anticipating extreme weather events that have significant social and economic impacts at S2S timescales, such as:

- Prolonged heatwaves
- Cold spells
- Droughts
- Heavy precipitation
- High wind conditions

Unlike short-term weather forecasts, which provide *deterministic* predictions – i.e., specific temperature, precipitation, and wind values for a given location, S2S forecasts are largely *probabilistic*. This means they explicitly offer a range of particular weather patterns that could occur rather than the specific values shown by deterministic forecasts. The challenge of predicting extreme weather at S2S timescales is especially pronounced since extreme events are rare and driven by complex interactions across different components of the climate system.

What Drives S2S Weather Patterns?

Scientists use recurring, quasi-stationary flow patterns called modes of climate variability to describe the large-scale atmospheric circulation. This is a core principle of S2S forecasting. These recurrent flow patterns of upper-level ridges and troughs shape temperature and precipitation trends across mid- and high-latitude regions, including Oklahoma.

Modes of climate variability evolve amidst differing background states of the climate system structured by other larger-scale, slower-evolving climate phenomena, such as:

- **The Madden-Julian Oscillation (MJO):** An eastward-moving pattern of tropical thunderstorms that moves around the equator and influences weather locally and elsewhere across the globe (**Figure 6.2**).
- **El Niño–Southern Oscillation (ENSO):** A recurring warming (El Niño) or cooling (La Niña) of the tropical Pacific Ocean, which has widespread impacts on atmospheric circulation and seasonal weather trends (**Figures 6.3a and b**).

- **The Stratospheric Polar Vortex:** A high-altitude (10–50 km above the surface) counterclockwise circulation in the Arctic that appears during the winter months. When the vortex is strong (i.e., strong winds and circular in shape), the jet stream (i.e., storm track) remains further north and cold air remains at high latitudes in the Arctic. When the vortex is disturbed/weakened, the jet stream below shifts southward, allowing cold air to invade the middle latitudes and sometimes extreme winter storms (**Figure 6.4**).

Understanding and predicting the evolution of these cross-scale interactions is critical for improving S2S predictions. However, this task is made even more complex by climate change, which is altering the frequency, intensity, and behavior of extreme weather events^{8,9}. As warming continues, historical weather patterns may shift, requiring ongoing refinements to S2S forecasting models to keep pace with these changes. By improving our ability to predict weather conditions weeks to months in advance, S2S forecasting has the potential to enhance disaster preparedness, optimize energy and agricultural planning, and support more resilient decision-making in the face of a changing climate.

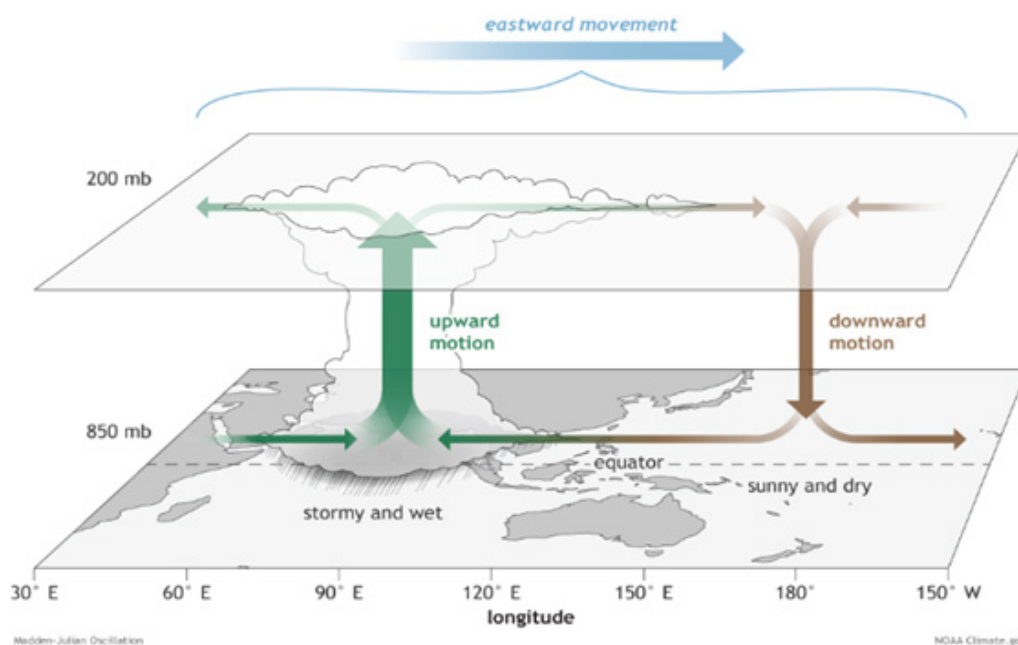
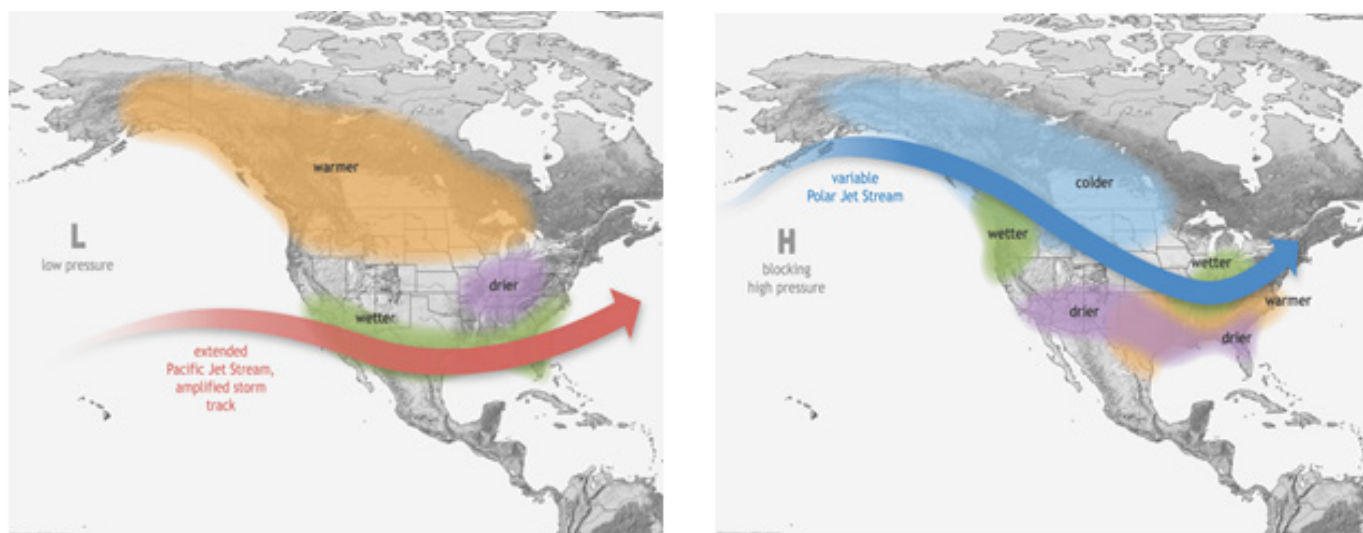


Figure 6.2. Illustration of the Madden-Julian Oscillation, a couplet of stormy and wet conditions and relatively dry conditions both upstream and downstream of the rainy area. *Courtesy of NOAA.*



Figures 6.3a and b. ENSO creates widespread seasonal weather trends based on El Niño or La Niña patterns. *Courtesy of the National Weather Service.*

Understanding the polar vortex

The Arctic polar vortex is a strong band of winds in the stratosphere, surrounding the North Pole 10–30 miles above the surface.

The polar vortex is far above and typically does not interact with the polar jet stream, the flow of winds in the troposphere 5–9 miles above the surface. But when the polar vortex is especially strong and stable, the jet stream stays farther north and has fewer “kinks.” This keeps cold air contained over the Arctic and the mid-latitudes warmer than usual.

Every other year or so, the Arctic polar vortex dramatically weakens. The vortex can be pushed off the pole or split into two. Sometimes the polar jet stream mirrors this stratospheric upheaval, becoming weaker or wavy. At the surface, cold air is pushed southward to the mid-latitudes, and warm air is drawn up into the Arctic.

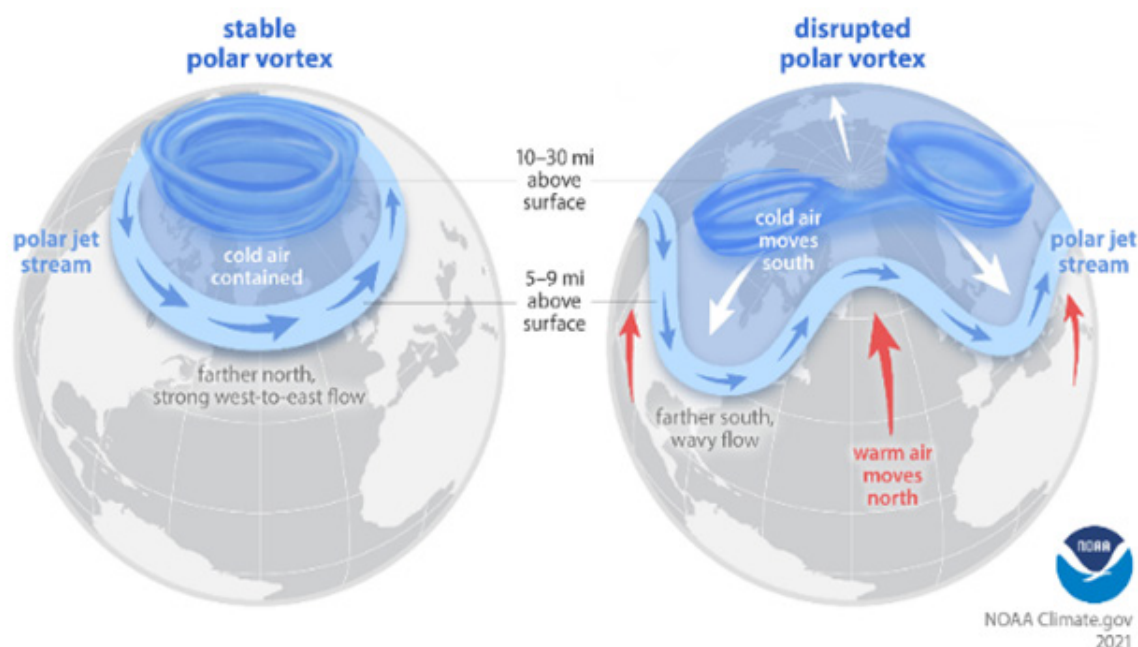


Figure 6.4 The *Stratospheric Polar Vortex*, though it resides tens of kilometers above the surface in the Arctic, can influence the jet stream below and affect temperature and precipitation patterns across the Northern Hemisphere. *Courtesy of NOAA.*

Improving S2S Forecasting

To improve the accuracy and usability of S2S weather forecasts, researchers within the S3OK project focused on improving our understanding of the fundamental processes that drive S2S weather patterns. Their work spans three key areas:

1. Identifying the mechanisms behind shifts in S2S variability.
2. Improving models' predictive skill for critical S2S phenomena.
3. Developing innovative S2S datasets to support resource management and infrastructure resilience in Oklahoma.

Oklahoma provides an ideal natural laboratory for advancing S2S forecasting due to the year-round nature of its highly dynamic, variable, and extreme weather conditions. The region experiences frequent and abrupt temperature swings, severe storms, droughts, and other extreme weather events that challenge existing forecasting capabilities. By improving S2S predictability in Oklahoma, researchers aim to develop insights that can be applied more broadly to other regions facing similar climatic variability. Three primary research areas underpin S3OK's contributions to advancing S2S insights:

- **Temperature Extremes** – Investigating patterns and drivers of prolonged heatwaves and cold spells to improve early warning systems.
- **Flash Droughts** – Understanding the rapid onset of drought conditions, their precursors, and their potential predictability.
- **Weather Precipitation Whiplashes** – Examining the causes and consequences of sudden shifts between extreme wet and dry conditions.

S3OK is shaping the future of forecasting and its applications for resilience planning. The following sections will summarize key findings from selected projects, focusing on:

- Temperature extremes
- Heatwaves
- Cold air outbreaks and temperature whiplash
- Flash droughts
- Precipitation whiplashes

Improving S2S Forecasting of Extreme Temperatures in Oklahoma

Oklahoma's geographic location makes it particularly susceptible to large temperature variability throughout the year. During the warm season, intense and prolonged heatwaves, influenced by heat transport from both the Gulf of Mexico, recently renamed the Gulf of America, and the Desert Southwest. During the cold season, extremely cold Arctic air masses can emerge southward from Canada and rapidly move south and eastward (the Rockies act as a natural barrier for the cold, dense air), introducing extremely cold temperatures.

With the relatively warmer, more moist air mass to the south, storm systems that pass nearby during these cold air intrusions can tap into this moisture, creating snow and ice storms that introduce multiple risks to Oklahoma's agriculture, roadways, and energy and water infrastructure. To build better resilience and preparedness for these extreme temperature impacts in Oklahoma, the S3OK team sought to improve forecast skill for both extreme heat *and* cold on S2S timescales.

Heatwaves

Oklahoma is no stranger to extremely hot temperatures during the summer. Additionally, the region's summertime circulation patterns, which frequently feature persistent high-pressure systems, foster extreme temperatures by enhancing solar radiation and drying out the land surface. Temperatures of 90°F or higher occur, on average, about 60–65 days per year in the western panhandle to about 115 days in southwest Oklahoma¹⁰ (OCS, 2025). Western Oklahoma experiences about 40 days at or above 100°F, decreasing to about 15 days per year as you head eastward¹⁰ (OCS, 2025). Moreover, with climate change driving temperature increases and

amplifying its variability, the risk of more frequent, longer-lasting, and more severe heatwaves is ever-present⁹.

To address these concerns, the S3OK S2S research team focused on two key areas:

1. **Reexamining how heatwaves are defined and determined**, particularly in the context of human health and environmental impact.
2. **Examining the rise of winter heatwaves** (“warm spells”) and their socioeconomic consequences in Oklahoma.

Reexamining Heatwaves using Wet Bulb Globe Temperature

Traditional definitions of heatwaves often focus on air temperature alone, but this approach overlooks other critical factors affecting heat stress, such as humidity, solar radiation, and wind speed¹¹. Davis et al. (2024)¹¹ tackled this issue by analyzing heatwaves using **Wet Bulb Globe Temperature (WBGT)**, a more comprehensive metric that incorporates multiple atmospheric variables to assess the true risk to human health (**Figure 6.6**). According to WBGT standards, values exceeding 88°F pose a high to extreme risk to human health during outdoor exposure.

Key findings from the study include:

- The frequency of high- and extreme-risk WBGT days in the Southern Great Plains has tripled over the past ~60 years.
- The greatest absolute increases in WBGT are occurring during winter months, signaling a potential lengthening of the warm season.

Examining the Emergence of Winter Heatwaves

Grace et al (2024)¹² analyzed the increase in winter heatwaves or warm spells throughout the Southern Plains region. The study highlighted a notable rise in the frequency and intensity of winter heatwaves, with an exceptional case occurring in December 2021. These events, while less studied than summer heatwaves, can have profound agricultural, ecological, and

socioeconomic impacts, disrupting winter crop cycles, increasing wildfire risk, and straining energy resources due to sudden fluctuations in heating and cooling demands.

Understanding and Improving S2S Forecasting of Heatwaves in Oklahoma

One of the primary obstacles in subseasonal forecasting is the limitations of current operational S2S models in predicting heatwaves beyond two weeks^{11,12}. This limitation is largely due to model difficulties in capturing North American weather regimes—persistent, recurrent atmospheric patterns that influence regional temperatures.

However, S3OK research identified key opportunities for improving S2S heatwave predictions:

1. Identifying “forecasts of opportunity”—or specific times when forecast skill improves relative to the mean skill. One such “forecast of opportunity” is above average MJO activity in the Indian Ocean and Maritime Continent, which has strong links to heatwaves in the Southern Great Plains¹¹.
2. Identifying and predicting the evolution of specific North American weather regimes in the S2S models^{11,12}.

The findings from these studies underscore the urgent need for improved S2S forecasting of heat extremes, particularly as climate change alters the frequency, duration, and intensity of both summer and winter heatwaves. By refining heatwave definitions, leveraging new predictive indicators, and identifying windows of enhanced forecast skill, researchers are paving the way for more actionable, extended-range forecasts.

Cold Air Outbreaks and Temperature Whiplash

Despite winters overall getting warmer on the average, extreme cold temperatures still occur and can have tremendous impacts. The most recent example was in February 2021, when for about two weeks, extremely low temperatures and

several inches of snow caused tremendous strains on water, transit, and electricity infrastructure¹³. Because of events like February 2021 and others in the recent past, the S3OK research team made significant strides in improving long-range forecasting of **cold air outbreaks (CAOs)** and **temperature whiplash events**, two phenomena that pose substantial challenges for forecasting and preparedness.

Identifying New Sources of Predictability of CAOs

To improve long-range predictions of extreme cold air outbreaks, Millin et al. (2022)¹⁴ developed the first-of-its-kind CAO database for the Central U.S., extending back to 1950. Their research identified two primary weather regimes associated with CAO formation:

1. **The Arctic High Regime:** Characterized by higher-than-normal pressure throughout the Arctic and over to Greenland, leading to deep cold air intrusions into the Central and Eastern U.S.
2. **The Alaskan Ridge Regime:** Defined by a blocking high-pressure system over the Gulf of Alaska, which redirects Arctic air southward into the Plains. This regime is associated with some of the most intense CAOs across the Central US over the last 75 years.

Recognizing these weather regimes, the study also linked their formation to key subseasonal predictors, providing advance warning up to 14 days before a CAO event:

1. Arctic **High CAOs** are often preceded by a weakened stratospheric polar vortex, which shifts the jet stream southward and makes it “wavier.” The result is higher-than-normal pressure over the Arctic and the expulsion of frigid air out of the Arctic and into the middle latitudes, including the Central US. Because of the strong high across the Arctic, these CAOs tend to be longer-lasting.
2. Alaskan **Ridge CAOs** are influenced by changes in tropical convection and another

phenomenon known as stratospheric wave reflection, whereby wave energy moves upward over Siberia but is then redirected eastward and downward over Canada. Both of those processes promote a stronger high pressure system over Alaska, resulting in southward flow of Arctic air down the US Plains. Wave reflection is particularly unique and interesting because the mechanism requires a stronger than normal stratospheric polar vortex, which differs from the prevailing paradigm and what we see for Arctic High CAOs.

The team also took their knowledge of CAO formation mechanisms to connect North American weather regimes and peak energy demand in the Southwest Power Pool (SPP) region¹⁴. Since operational models have skill in forecasting these weather regimes up to 14–20 days in advance¹⁵, subseasonal weather regime forecasts could enhance energy load predictions and improve preparedness for wintertime energy demand surges.

Predicting Wintertime Temperature Whiplash Events

Sudden swings from anomalously warm to anomalously cold temperatures (or vice versa) over just a few days, known as “temperature whiplashes,” can have severe socioeconomic consequences, including infrastructure damage, agricultural losses, and increased energy demand volatility. Research by Giannakopoulos and Furtado (2025)¹⁶ defined and characterized temperature whiplash events across the US Southern Plains during the winter. Their findings indicate a notable increase in “hot-to-cold” whiplash events since the 1990s, underscoring the growing climate variability in the region.

Key subseasonal predictors of these “hot-to-cold” whiplash events for the Southern Plains mirrored some of the same found for CAOs (1) The Alaskan Ridge regime prior to the event, which disrupts normal weather patterns and allows cold air to move southward.; and (2) wave reflection, which reinforces high pressure near Alaska and Canada.

These characteristics present forecasts of opportunity, meaning that S2S models may have enhanced skill in predicting whiplash events under certain atmospheric conditions.

Implications for S2S Forecasting and Climate Resilience

The findings from the above-mentioned studies highlight promising avenues for improving subseasonal forecasting of extreme temperature events, particularly through weather regime-based forecasting strategies. By leveraging these new insights, the S3OK research team is bridging the gap between weather and climate predictions, advancing more reliable tools for managing weather extremes in a changing climate. With continued advancements in S2S modeling, researchers aim to:

- Enhance early forecasting for CAOs, heatwaves, and temperature whiplash events.
- Improve energy demand forecasting, particularly in vulnerable grid regions like the Southwest Power Pool (SPP).
- Provide decision-makers with more actionable insights to mitigate the socioeconomic impacts of extreme temperature swings.

Flash Droughts: Understanding Their Increasing Frequency and Predictability Challenges

Unlike traditional droughts, which develop gradually over months or years, flash droughts emerge suddenly and intensify rapidly, driven by a combination of critical precipitation deficits and elevated evaporative demand. These events are often amplified by atmospheric conditions like blocking highs, periods of time when areas of high pressure over the region remain quasi-stationary for several days to weeks, keeping the weather very warm, sunny, and dry. Oklahoma's diverse landscape and complex seasonal weather patterns make it especially vulnerable to these rapid-onset droughts.

Key findings from Christian et al. (2023a)¹⁷ indicate that flash drought occurrences are

increasing globally due to climate change, with large increases projected in North America and Europe under high-emission scenarios. This trend raises concerns for agriculture, water supply, and ecosystem stability in Oklahoma and other drought-prone regions. Fellman et al. (2025)¹⁸ investigated these flash drought events over the Southern Great Plains and their potential impact of flash drought events on winter wheat productivity in the region. Results indicate that flash drought events from July to October, just before and during the planting of winter wheat, have the most significant negative impacts on winter wheat productivity the following spring in Oklahoma. These events deplete the soil moisture contained in the ground, and cause below-average soil moisture conditions to persist throughout much of the growing season due to limited precipitation experienced during the winter months.

Forecasting flash droughts on the S2S timescale using existing dynamical models remains a challenge. Christian et al. (2024)¹⁹ highlighted difficulties in implementing specialized flash drought indices into operational forecasts, as flash droughts exhibit distinct seasonal patterns (peaking in spring and early summer for Oklahoma). As such, flash droughts remain challenging to predict on subseasonal timescales. In an analysis of the 2022 flash drought events, Christian et al. (2024)²⁰ found that current subseasonal prediction models underestimated both the speed of onset of these events. A major limitation was the inability of models to accurately simulate land-atmosphere interactions, a critical component in the rapid intensification of drought conditions.

Precipitation Whiplashes: Advancing S2S Forecasting of Precipitation Extremes in Oklahoma

Oklahoma's highly variable climate makes it particularly susceptible to rapidly developing droughts and extreme precipitation swings. Understanding these phenomena at the S2S scale is essential for improving disaster preparedness, water resource management, and

agricultural planning. The S3OK research team has made significant progress in advancing the prediction and characterization of two critical hydrometeorological hazards: flash droughts and precipitation whiplash events.

Predicting Rapid Shifts Between Extremes: The Challenge of Precipitation Whiplash Events

Oklahoma sits at the convergence of arid western and humid eastern North America, resulting in a sharp zonal precipitation gradient (**Figure 6.5**; PRISM Climate Group, 2004). As a result of its unique geography, Oklahoma experiences annual precipitation values that vary as much as 50 to 60 in. in the southeast of the state to 16 to 20 in. in the northwest. This divide, however, can change on subseasonal to interannual scales^{21, 22, 23, 24, 25}, making Oklahoma prone to rapid transitions in precipitation extremes.

As a result, Oklahoma is also prone to precipitation whiplash events—sudden transitions between extreme wet and dry conditions²⁶. These events can lead to severe cascading impacts, including:

- Wildfire outbreaks following anomalously wet periods^{27, 28, 29, 30}
- Flash drought development due to rapid drying^{27, 28, 29, 30}
- Decreased water quality from hydrological shifts^{27, 28, 29, 30}
- Flash flooding from sudden heavy rainfall events^{27, 28, 29, 30}

Given the profound impact each of these precipitation whiplash events has on the economy, agriculture, and social well-being, the challenge and need for predicting these rapid shifts between extremes is urgent.

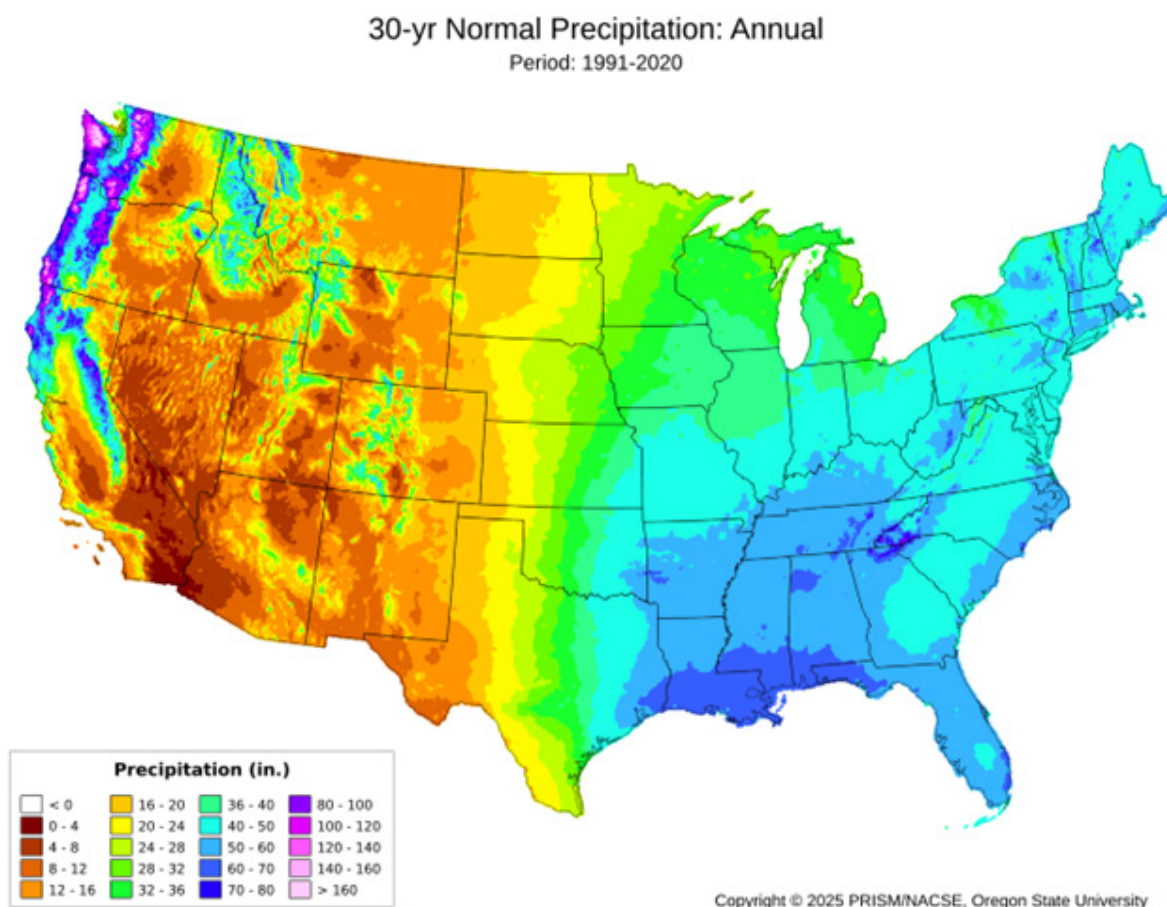


Figure 6.5. 30-year (1991–2020) climatological mean annual precipitation (in) across the Contiguous 48. Data from PRISM. Note that across Oklahoma, there is a very sharp east-to-west change in the average annual precipitation.

Linking Precipitation Abnormalities to Wildfire Risk

In a study of wildfire risk across Oklahoma, Puxley et al. (2024)³¹ investigated the role of preceding precipitation anomalies in fueling extreme fire seasons. Their analysis revealed a strong lag correlation between high precipitation 8 months prior and increased wildfire frequency and acreage burned in the following spring.

The study identified a distinct wet-to-dry transition pattern in seasonal precipitation anomalies, in which:

- Above-average spring vegetation growth, driven by excessive rainfall, creates abundant fuel for future fires.
- An anomalously wet summer followed by a dry winter reduces vegetation moisture, making conditions highly flammable by the next spring.

These findings provide valuable insights for wildfire forecasting and could provide a valuable tool for decision-makers seeking to develop longer-term fire management strategies based on subseasonal precipitation trends across Oklahoma.

Defining and Predicting Precipitation Whiplash Events at the S2S Timescale

S3OK researchers Puxley and Martin (2025)³² are working to define precipitation whiplash events using the standardized precipitation index (SPI) with 30-day rolling precipitation accumulation totals. Once identified, their research aims to examine:

- Climatology of precipitation whiplash events in Oklahoma.
- The synoptic drivers responsible for these rapid transitions.
- The relationship between precipitation whiplash events and wildfire and flood risks.
- How these dynamics might change in the future.

Improving S2S Forecasting and Climate Adaptation

The S3OK research on flash droughts and precipitation whiplash events highlights the urgent need for more reliable S2S forecasting tools that can anticipate rapid hydrometeorological shifts. By improving our understanding of land-atmosphere interactions, atmospheric blocking patterns, and precipitation variability, researchers can help inform more effective early warning systems for droughts, floods, and wildfires.

Future work will focus on refining predictive models, integrating subseasonal atmospheric indicators, and enhancing decision-making frameworks to mitigate the socioeconomic and environmental impacts of these extreme events. As Oklahoma continues to experience increasing climate variability, these efforts are critical for building climate resilience across the region.

Social Dynamic Considerations of S2S

Understanding the social dynamics of S2S weather phenomena is essential for improving resilience to extreme climate events. S2S extremes can have profound socioeconomic consequences, disrupting agriculture, energy demand, public health, and infrastructure systems.

However, the impacts of these events are not solely physical; they are deeply intertwined with public perception, awareness, and preparedness. The ability of communities, industries, and policymakers to respond effectively to S2S weather extremes depends on how well these risks are communicated and understood. Misinformation, lack of predictive confidence, or low public trust in forecasts can hinder proactive decision-making, increasing vulnerability.

As climate variability intensifies, maintaining current insight into the social dimensions of S2S phenomenon is crucial in ensuring that scientific advancements translate into actionable

strategies for reducing societal risks. This section details collaborative work advanced that provides insight into public perceptions of S2S extreme events:

- Assessing public understanding of S2S forecasting for extreme events
- Evaluating public perceptions and socioeconomic impacts of S2S extreme events
- Bridging the gap between perception and reality
- Understanding awareness of drought through digital behavior
- Assessing implications for policy and risk communication

Assessing Public Understanding of S2S Forecasting for Extreme Events

As noted above, S2S forecasts are becoming increasingly accurate, yet their societal benefits remain poorly understood. Key questions—who might use them, for what purposes, and under what circumstances—have yet to be fully addressed. To begin exploring these questions, an S3OK study³³ surveyed Oklahomans, yielding the following key findings:

- **Awareness of S2S forecasts is limited:** Just over half of Oklahomans (57.3%) were aware that S2S forecasts for temperature and precipitation are currently available.
- **Usage among those aware is low:** Among Oklahomans familiar with S2S forecasts, just 19% reported using them “regularly” or “frequently.” Most relied on local TV or non-government websites for access. Common applications included planning for travel, outdoor activities, and agriculture or gardening.
- **Perceptions of accuracy and relevance were key barriers:** Thirteen percent of respondents viewed current S2S forecasts as too inaccurate or unreliable, while 10% were unsure how these forecasts aligned with their daily needs.
- **Support for further investment was strong:** Despite low awareness and concerns, 70% of Oklahomans said they would vote in favor of

improving S2S forecasts if there were no cost to them. Of those who said they would vote in favor of improving S2S forecasting if there were no cost to them, over 50% expressed willingness to support such a proposal even if it incurred a cost of up to \$20 annually for the next decade. Additionally, more than 60% indicated they would use S2S forecasts if improvements were made.

Evaluating Public Perceptions and Socioeconomic Impacts of S2S Extreme Events

Beyond assessing public understanding of S2S forecasting, insight into how people perceive and respond to subseasonal-to-seasonal extreme events plays a critical role in shaping societal resilience and adaptation strategies. While meteorological records and key science advanced by S3OK research on S2S provide objective measurements of extreme events, public awareness and concern often do not align with actual climate trends. This misalignment has important implications for disaster preparedness, policy responses, and risk communication.

Bridging the Gap Between Perception and Reality

S3OK researchers leveraged survey data and meteorological records to analyze the discrepancies between public perception and observed climate extremes using statistical analysis and spatial visualization techniques. They found that:

- The public is more concerned about sudden, high-impact events like tornadoes but is less aware of slow-developing climate phenomena, such as droughts.
- Despite their devastating long-term consequences, droughts receive less public attention, likely due to their gradual onset and cumulative impacts.
- Public education and outreach efforts need to be expanded to increase awareness of slow-onset but intensifying climate extremes.

Understanding Awareness of Drought Through Digital Behavior

Another study examined public awareness of droughts by analyzing Google Trends search data alongside the U.S. Drought Monitor (USDM) records. The study found:

- People generally do not respond to moderate drought conditions, likely because they do not perceive immediate impacts on daily life.
- There is an average two-week delay in public attention to severe drought conditions, indicating that awareness only increases once tangible impacts—such as water restrictions or crop damage—become evident.
- This delayed response suggests that individuals are reacting reactively rather than proactively to droughts, highlighting the need for improved communication strategies and early warning systems to enhance preparedness.

Assessing Implications for Policy and Risk Communication

These findings emphasize the complex social dimensions of S2S climate extremes, demonstrating that public perceptions do not always align with meteorological reality. As climate variability increases, it is essential to:

- Develop targeted public outreach campaigns that emphasize the long-term consequences of slow-onset climate events.
- Improve early warning systems and communication strategies to engage communities before extreme events reach crisis levels.
- Enhance cross-sector collaboration between scientists, policymakers, and local communities to translate S2S forecasts into actionable strategies for risk reduction.

By integrating social science insights with meteorological advancements, S3OK research is helping to close the gap between perception and reality, fostering more informed decision-making

and resilient communities in the face of S2S climate extremes.

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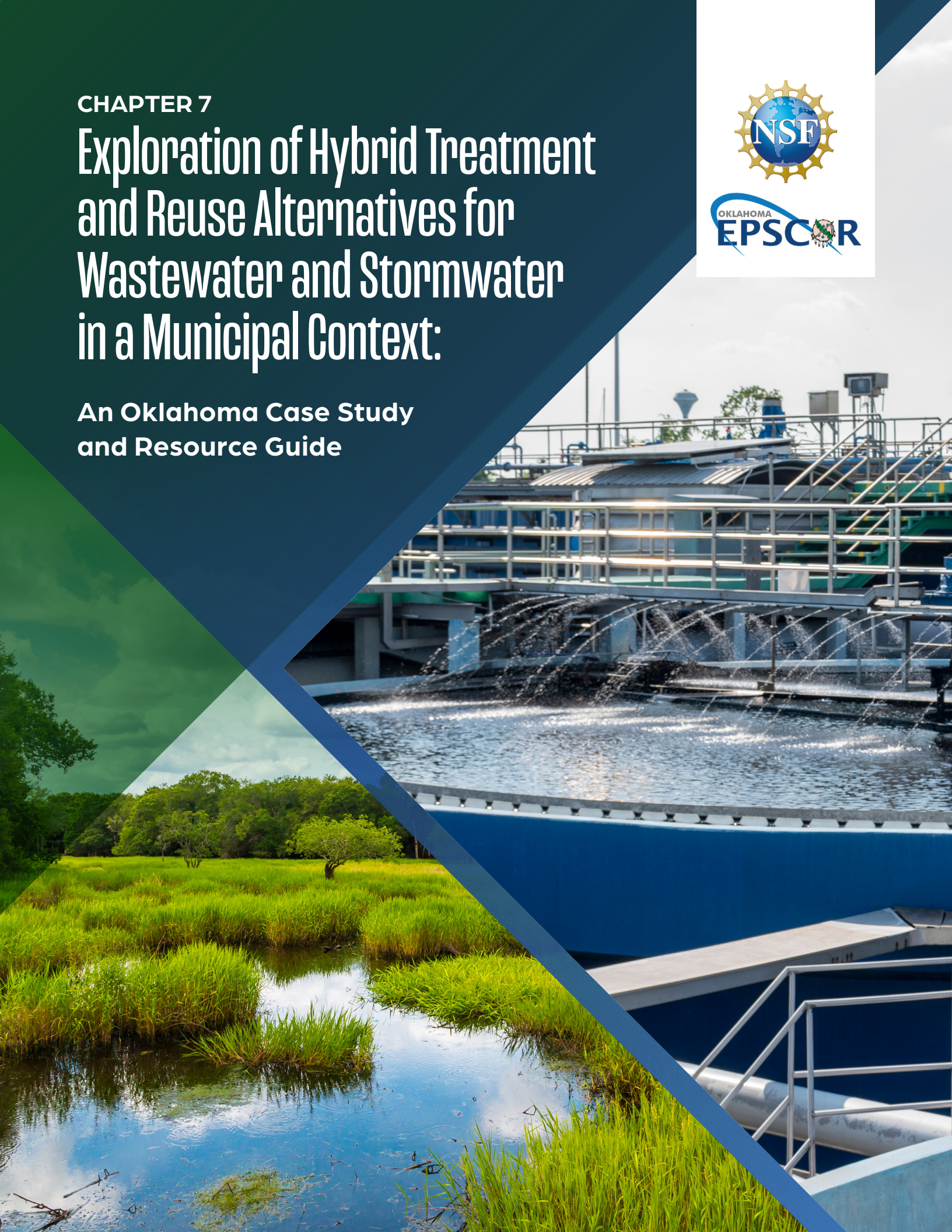
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CHAPTER 7

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

An Oklahoma Case Study and Resource Guide



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97	Rationale for Exploration of Novel Water Treatment and Reuse Approaches
98	Case Study: City of Norman
98	Drivers Motivating Norman’s Exploration of Hybrid Treatment and Reuse Systems
100	Strategic Opportunities for the City of Norman
101	Proposed Solutions Advanced for the City of Norman
104	Additional Solutions for Future Consideration
104	Municipal Wastewater
104	Enhanced Biodegradation of CECs for Municipal Water Quality
105	Catalysts for Advanced Oxidation Water Purification
106	Novel Oxidation Systems for Municipal Wastewater Treatment and Reuse
107	Advanced Oxidation Processes for Wastewater Reuse
107	Innovative Stormwater Treatment
108	Measurement of Surrogate CEC Test Compounds for Wastewater Reuse Systems
108	Technical and Regulatory Challenges and Other Considerations of Importance
108	Public Support and Willingness to Pay for Municipal Wastewater Reuse Programs
111	Regulatory Considerations
112	Sustainability
113	Plans for Future Technical Work
114	Catalysts
114	Co-Treatment of Wastewater and Stormwater
115	Cost-Benefit Analysis of Water Treatment and Reuse Approaches
115	Concluding Guidance
116	References

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

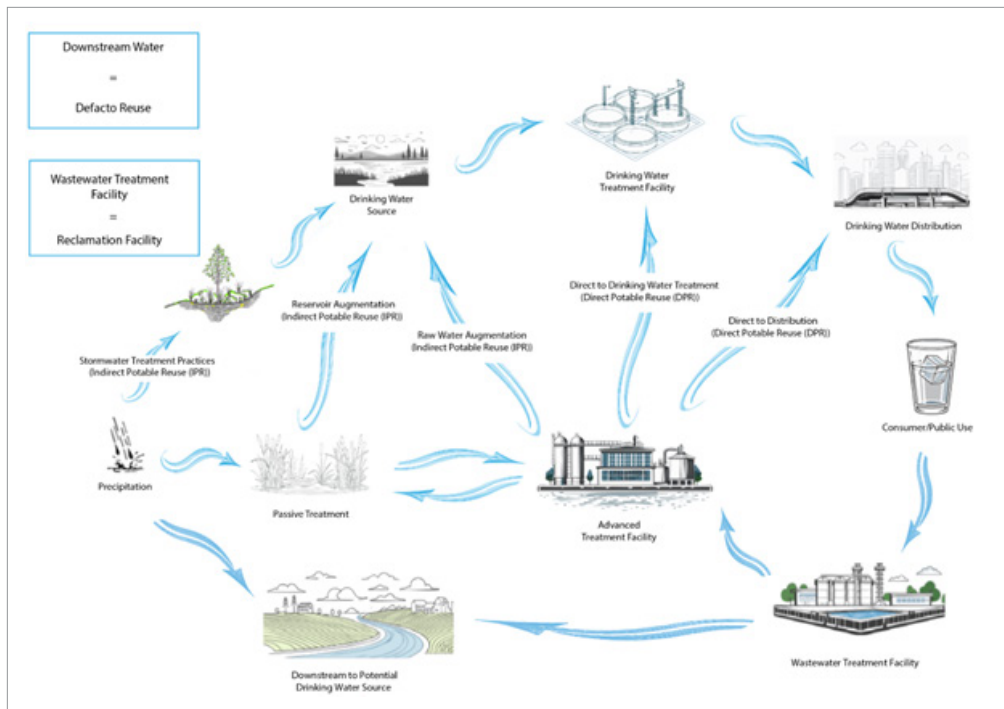


Figure 7.1. A hypothetical treatment and reuse diagram demonstrating potential pathways for treatment and reuse.

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 projections⁶ indicate that demands on the Norman water system may soon outpace water supply¹. 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 system⁴ 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.

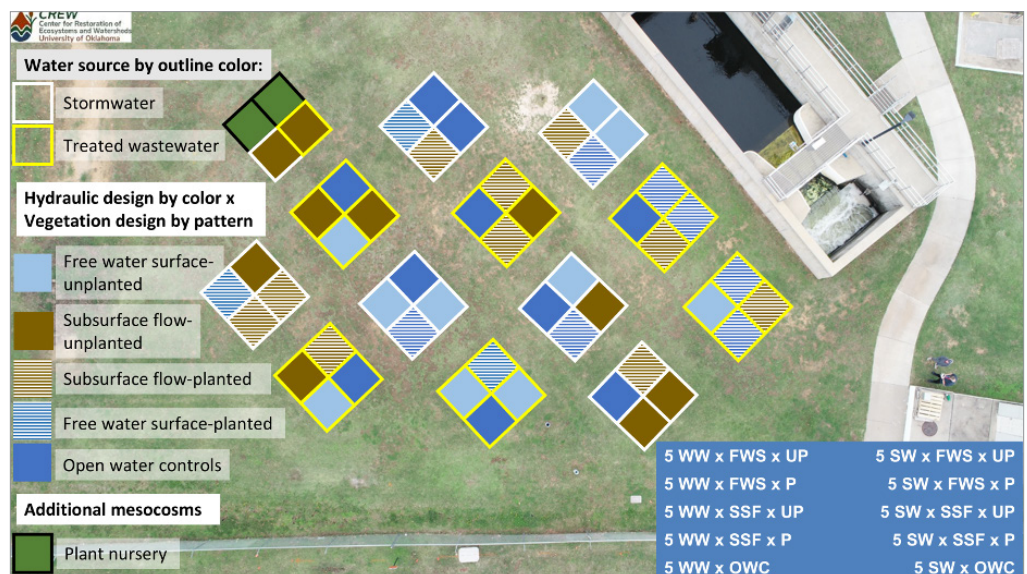
An initial experiment examined the critical role of hydraulic retention time (HRT) in treatment performance. Based on the treatment wetlands literature, three HRTs—three, seven, and 10 days—were examined. Changes in concentrations of conventional constituents (e.g., solids, nutrients) and carbamazepine 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 processes¹². 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



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

role of active aeration was found to be negligible.

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 CECs⁵—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. 2017²⁵, "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 NWRP. 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 (O_2) and hydrogen peroxide (H_2O_2) 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

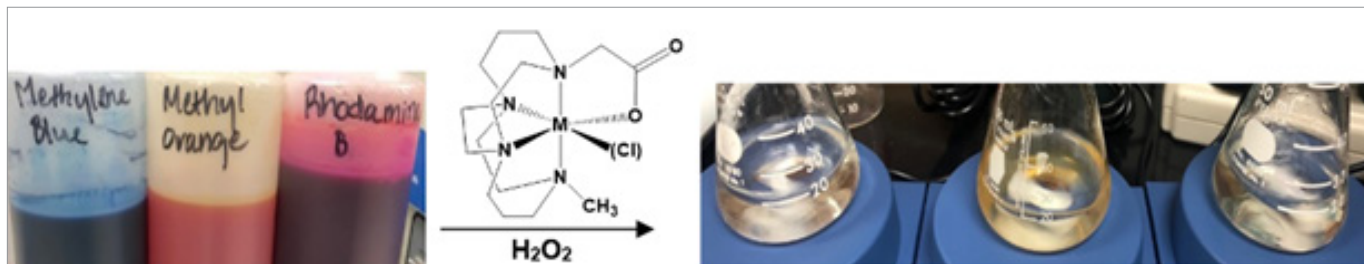


Figure 7.6. Common dye pollutants Methylene Blue, Methyl Orange, and Rhodamine B before (left) and after (right) catalytic oxidation by macrocyclic catalysts using hydrogen peroxide.

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.

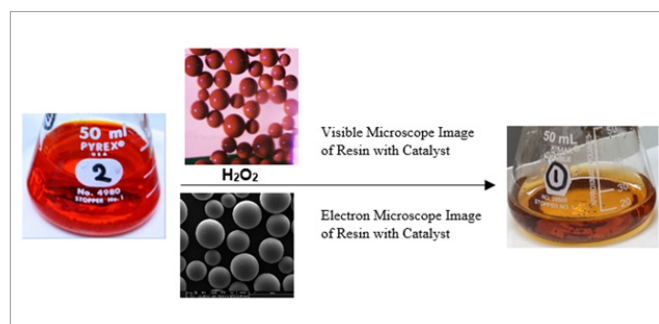


Figure 7.7. Methyl Orange dye in a reaction flask with solid state resin catalyst prior to oxidative destruction (left), optical and scanning electron microscope images of the resin catalyst (center), and significantly reduced coloration of the same dye after catalytic oxidation (right).

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).

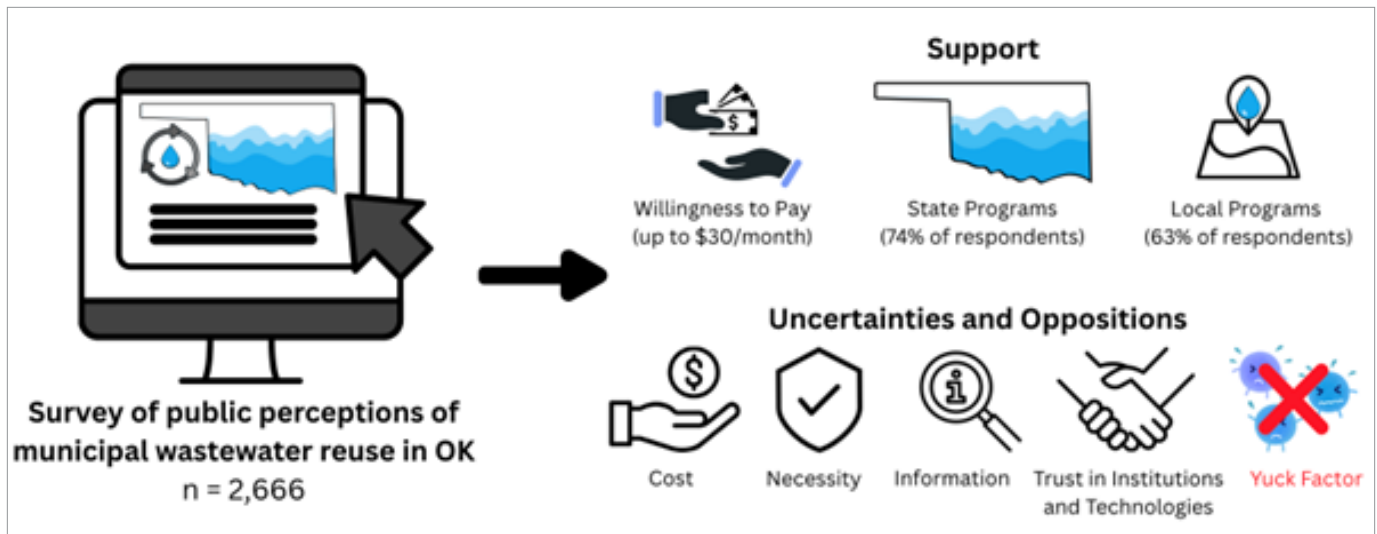


Figure 7.8. Diodosio et al. 2025 showed varying degrees of support for wastewater reuse options.

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%).

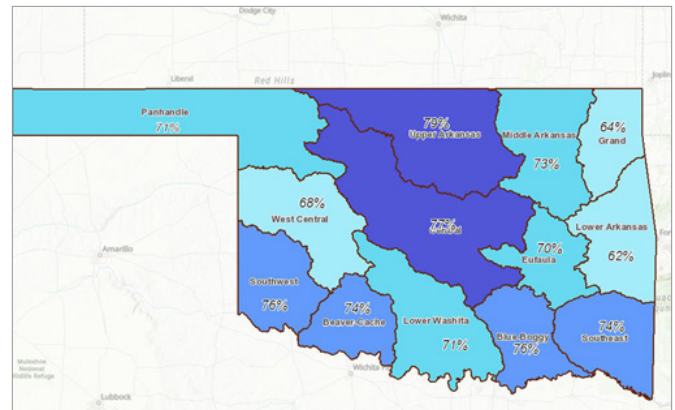


Figure 7.9. Map of percentage of public support (i.e., a vote in favor) for a statewide program that would offer financial assistance to cities, towns, and municipalities implementing municipal wastewater reuse projects, by OCWP Watershed Planning Regions.

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

Steps of the Life Cycle Assessment (LCA)

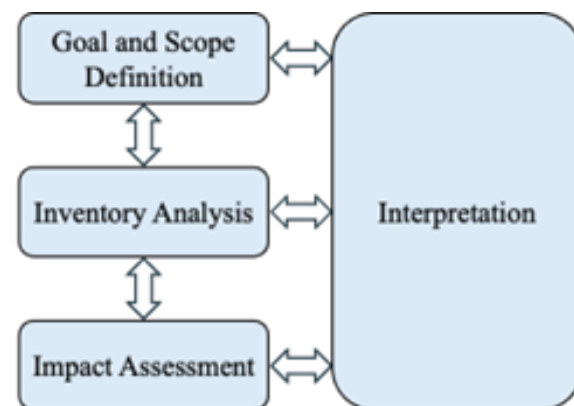


Figure 7.10. Steps of life cycle assessment.

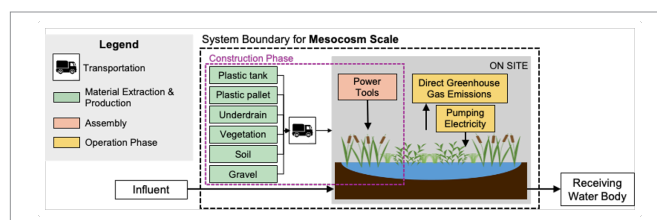


Figure 7.11. System Boundary for Mesocosm Scale.

mesocosms to quantify and compare life cycle environmental impacts associated with the different system designs.

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/>

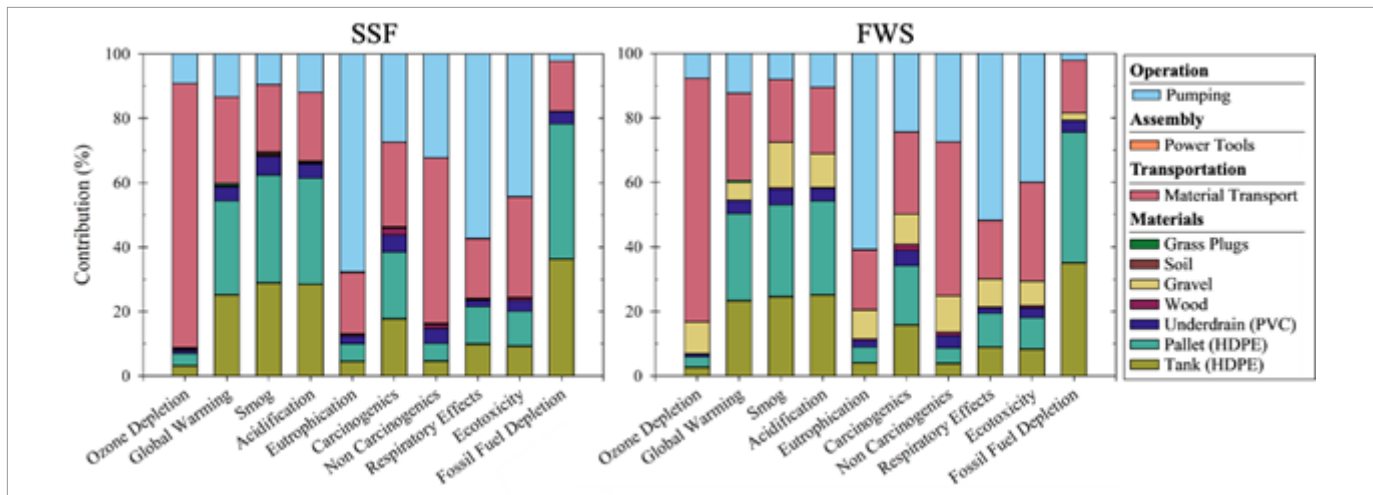


Figure 7.12. LCA results by inventory item for the subsurface flow (SSF) and free water surface (FWS) wetland mesocosms. Values reflect median results from uncertainty analysis, normalized to percent contribution for each impact category.

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.

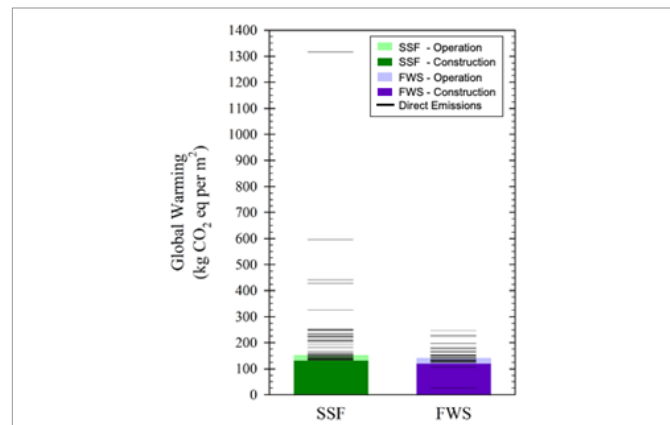


Figure 7.13. Lifetime global warming impact results for the subsurface flow (SSF) and free water surface (FWS) wetland mesocosms. Black bars represent direct emission data, collected from a literature review and converted to CO₂ equivalent over a lifetime of 20 years, added to the global warming results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

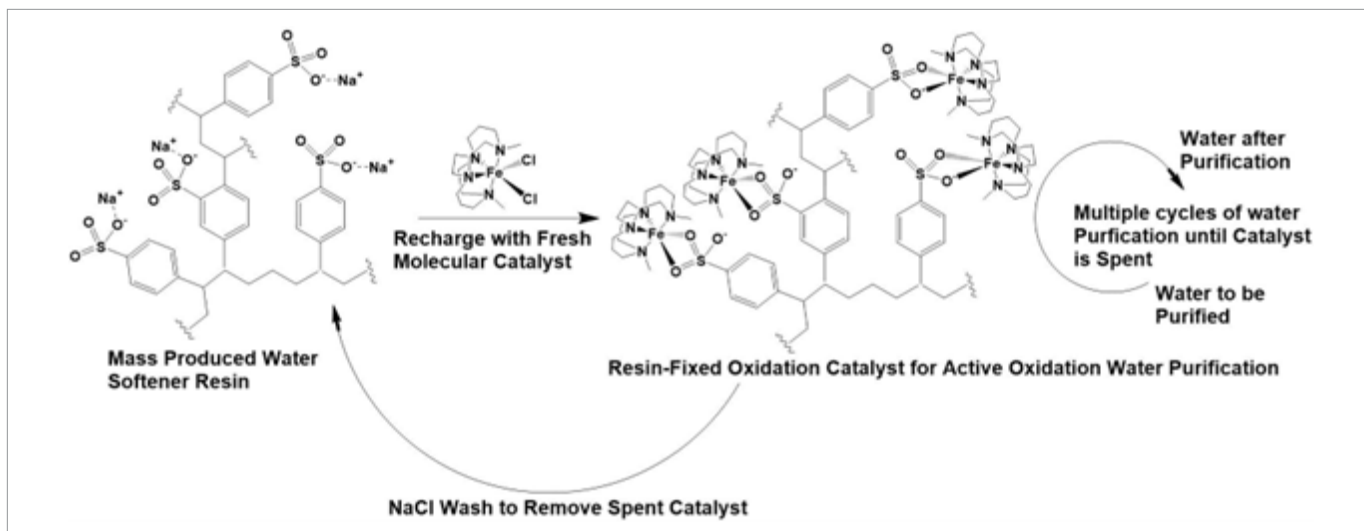


Figure 7.14. Proposed scheme for resin-based solid-state water purification by catalytic oxidation. The resin can be recharged by adding additional catalytic metal complex when it starts to be less effective (arrow at bottom). Likewise, the resin can treat a continuous flow of contaminated water (arrow 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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CHAPTER 8

Enhancing Water Availability for Agricultural and Oilfield Applications



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124	Enhancing Water Availability for Agricultural and Oilfield Applications
125	Nature of Water Quantity Problems
126	Produced Water Opportunities
127	Reduced Water Availability Related to Weather and Climate
127	Increasing Eastern redcedar encroachment
128	Reduced Soil Health
128	Key Science Advancements/Proposed Solutions to Reduced Water Availability
129	Eastern Redcedar (ERC) Encroachment
130	Reduced Soil Health
131	Produced Water Treatment, Resource Extraction, and Reuse
131	Microbial Pretreatment to Remove Hydrocarbon
131	Improving Pre-Treatment Oil-PW Separation Techniques
132	Membrane Distillation (MD)
135	Carbonated Produced Water for Enhanced Oil Recovery
135	Annotated Treatment Train for Produced Water
136	Future Work/Considerations
137	Current Regulatory Environment for PW Reuse in Oklahoma
137	Resource Recovery Potential
138	Potential Agricultural Use of Treated PW
139	Improved Treatment Cost, Economic Opportunities, and Environmental Benefit
140	PW Consortium/Regional Efforts
140	References

CHAPTER 8

Enhancing Water Availability for Agricultural and Oilfield Applications

In the summer of 2020, Oklahoma received a National Science Foundation EPSCoR award to conduct research and collaborate with practitioners to address particularly complex issues (“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 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 of high

relevance to Oklahomans and that this science could be applied directly to challenges currently faced by Oklahoma’s water sector.

Enhancing Water Availability for Agricultural and Oilfield Applications

Through the S3OK opportunity, researchers and OLAN members collaborated over five years 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 throughout years four and five of the project. Following a series of iterative selection processes, S3OK researchers and OLAN members decided to explore the topic of *Produced Water Reuse Potential for Oilfield and Agricultural Applications*.

Later, this focus was expanded to capitalize on S3OK research on improving soil health and management of Eastern Red Cedar, culminating in this chapter, *Enhancing Water Availability for Agricultural and Oilfield Applications*. Partners who contributed to this chapter’s work included:

S3OK emphasized not just research but systematic and iterative engagement between key stakeholders, the public, and researchers to identify convergent solutions in these key areas.

- Chickasaw Nation
- D&B Oilfield Services Inc.
- Noble Research Institute
- Oklahoma Department of Environmental Quality
- Oklahoma State University
- Oklahoma Water Resources Board
- University of Oklahoma

Nature of Water Quantity Problems

According to the 2012 Oklahoma Comprehensive Water Plan (OCWP), statewide consumptive demand for water will increase by 33% between 2010 and 2060. Much of this growing demand will occur in the crop irrigation sector. However, the oil and gas demand sector will experience the highest growth rate statewide, approaching 200%. Concurrently, surface water availability gaps, which occur when the demand for water is projected to exceed available supply, are forecasted in 67% of OCWP basins by 2060. At least minor depletions of alluvial and bedrock groundwater aquifers are predicted to occur in 78% and 41% of planning basins, respectively, by 2060 with many of these depletions occurring in western Oklahoma. Not surprisingly, the Oklahoma Meso-Scale Integrated Socio-Geographic

Network (M-SISNet), a longitudinal survey of up to 2,500 geolocated households across Oklahoma that provides data on household perceptions on various issues, found that a substantial portion of the Oklahoma public is concerned with water quantity issues (**Figure 8.1**). Per this survey, the western half of the state (particularly the southwest and Panhandle) perceive more issues with water quantity than other regions. This is consistent with the 2012 OCWP update, which found limited supply for growing demands in these regions.

To meet future demands, the 2012 OCWP recommends that the use of marginal quality water sources—such as brackish groundwater, treated wastewater effluent, production water from oil and gas operations, and stormwater runoff—have the potential to augment supply in many areas of Oklahoma. Similarly, the Working Group on *Enhancing Water Availability for Oilfield and Agricultural Applications* also identified **reuse of produced water**, or water that naturally exists in subsurface formations and is brought to the surface during oil and gas production, as a potential source of water to combat water scarcity. The current practice of produced water disposal was identified as a wasted opportunity for increasing water availability.

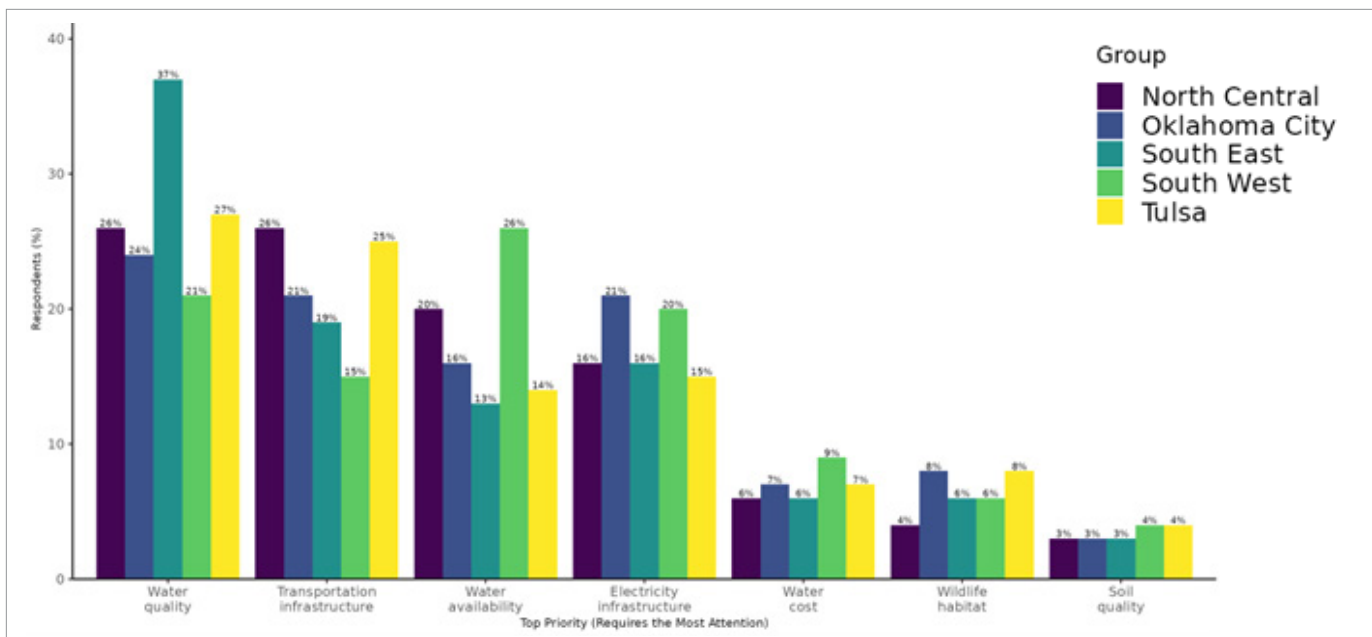


Figure 8.1. Oklahoma public responses to the question “If you were advising the scientists and policymakers who are working on this project, which of the following would you tell them require the most attention?”

Further, the Working Group identified three problems contributing to declining water availability to be addressed by S3OK Researchers (other challenges were noted, such as the need for water conservation, but other university researchers are addressing these thus it was determined that this work group not focus on them):

1. Reduced water availability due to changing weather/climate conditions
2. Increasing Eastern Redcedar encroachment contributing to water depletion
3. Reduced soil health due to past as well as present land management practices and changing climate conditions limiting water retention and agricultural land resilience to drought

Produced Water Opportunities

The oil and gas industry generates staggering volumes of wastewater which is called produced water (PW). PW includes both formation water and injection water. For every barrel of oil produced, nearly 9–10 barrels of PW (one barrel equals 42 gallons) are generated, totaling approximately 25 billion barrels per year in the US and 70 billion barrels globally^{1,2,3}. Oklahoma is a leading US oil and gas producer, resulting in large amounts of water brought to the surface alongside oil and natural gas production.

PW contains a variety of contaminants, including oil and grease, dissolved hydrocarbons (BTEX, PAHs, phenols), heavy metals, naturally occurring radionuclides, corrosion inhibitors, biocides, and fracking chemicals, all of which pose significant pollution and health risks^{4,5}. Additionally, PW often contains high levels of salt, ranging from <3% to over 30%. Conventional treatment methods are costly and often fail to meet environmental standards, as such, this water is generally disposed of via reinjection deep underground. Reinjection involves pumping the salt water into a porous geological layer capable of taking in the volumes of water. This layer is often deep, and high pressures are frequently required to pump the water into these deep layers. While we do

not have exact numbers for more recent years, nearly 1.5 billion barrels of PW were disposed of underground in Oklahoma in 2014 via saltwater disposal (SWD) wells⁶.

Deep well injection has become increasingly challenging due to stricter regulations, limited underground capacity, and the potential for seismic hazards^{7,8}. Depending on location and facility availability, SWD costs range from \$0.50 to \$2.50 per barrel. Transporting PW to disposal sites adds additional costs—typically \$1.00 per barrel for each hour of transport. Transport costs are lower in areas with abundant SWD facilities, around \$0.50 per barrel. However, in areas with fewer facilities, PW must be transported to distant facilities, resulting in additional costs of \$4.00 to \$6.00 per barrel.

In Oklahoma and other oil- and gas-producing regions, PW represents a significant opportunity to supplement stressed water supplies for agricultural and other beneficial uses. Some PW sources also contain valuable metals and minerals that, if recovered during treatment, could provide a revenue stream to support the adoption of PW treatment technologies.

Oklahoma's PW, in particular, contains rare and critical elements such as lithium, bromine, and iodine—resources with important industrial and technological applications. In addition to mineral recovery, certain volumes of PW may be suitable for treatment and reuse in applications like agricultural irrigation, aquifer storage, and rangeland restoration.

With this potential in mind, the S3OK initiative was launched to explore dual opportunities: treating PW for reuse and extracting valuable minerals. Researchers have made progress in key areas such as oil-brine, metal-brine, and freshwater-brine separations. These processes can be integrated into a treatment train designed to meet specific goals—whether for water recovery, mineral extraction, or both.

S3OK evaluated a range of treatment and extraction methods that can be tailored based on

the target resources and the desired water quality. In theory, this approach to resource recovery could create multiple economic incentives for the oil and gas industry to treat PW, ultimately enhancing regional water availability.

Reduced Water Availability Related to Weather and Climate

According to NOAA⁹, Oklahoma is located in the central Great Plains and spans a climate transition zone—from the wetter southeast, which receives over 50 inches of rain annually, to the drier, semi-arid west, which gets less than 20 inches. This geographic position results in a wide range of average daily temperatures. Since the early 1900s, the state has warmed by about 0.6°F. In recent decades, rising temperatures in Oklahoma, Texas, and Kansas have been accompanied by fewer but more intense rainfall events¹⁰.

Rainfall in Oklahoma varies greatly from year to year. The state has seen annual precipitation range from a low of 20.3 inches in 1910 to a high of 53.7 inches in 2015. The driest multi-year periods occurred in the 1910s, 1950s, and 1960s, while the wettest were in the 1990s and late 2010s. The driest five-year stretch was from 1952 to 1956, and the wettest was from 2015 to 2019. Most of the state's rainfall occurs in the spring and summer. Since 1985, the number of extreme rainfall events—those with 2 inches or more—has increased, peaking in 2015.

Droughts are a frequent and serious issue in Oklahoma. Since 2000, the state has been completely free of drought only about 21% of the time, while experiencing drought conditions over at least half its area about 28% of the time. Looking ahead, Oklahoma is expected to become warmer, with more intense heat waves and less severe cold spells. Although overall annual precipitation trends are unclear, summer rainfall may decrease slightly (**Figure 8.2**). Even if rainfall remains steady, higher temperatures will lead to more evaporation and drier soils, worsening droughts and increasing the risk of severe wildfires.

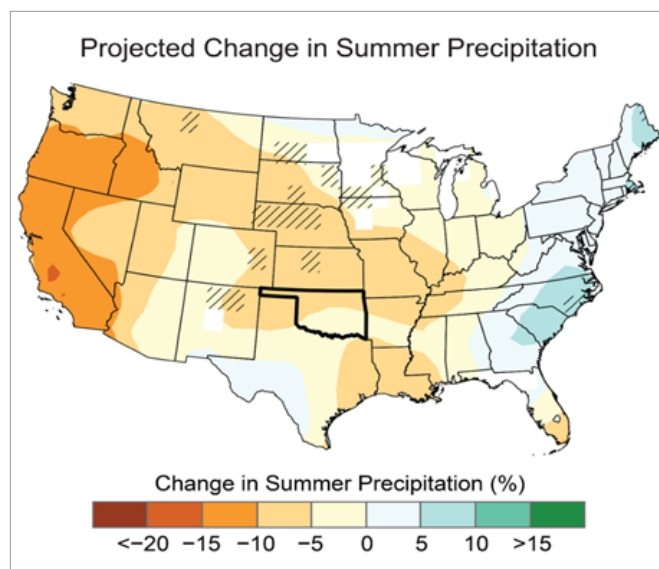


Figure 8.2. Projected change in summer precipitation (Courtesy of NOAA).

Increasing Eastern redcedar encroachment

Eastern redcedar (*Juniperus virginiana* L.) is a native evergreen tree that is rapidly encroaching upon the Great Plains, particularly the grasslands of Oklahoma. In recent years, evergreen species—especially junipers—have been expanding in Oklahoma at a rate five to seven times faster than in other regions of the United States.

As of 2018, Eastern redcedar covered more than 4.5 million hectares in Oklahoma, with projections estimating an increase to over 6.3 million hectares by 2028¹¹. Satellite imagery analysis conducted by our team revealed that between 2016 and 2020, Oklahoma's forested area grew by 243,893 acres (a 1.9% increase), primarily in the central and northeastern parts of the state.

This rapid expansion is largely driven by fire suppression and changes in land management practices, such as overgrazing and the abandonment of cropland. The encroachment of Eastern redcedar has had significant ecological consequences, including the displacement of native plant and animal species, reduced forage availability for livestock, altered soil hydraulic properties, and an increased risk of wildfires.

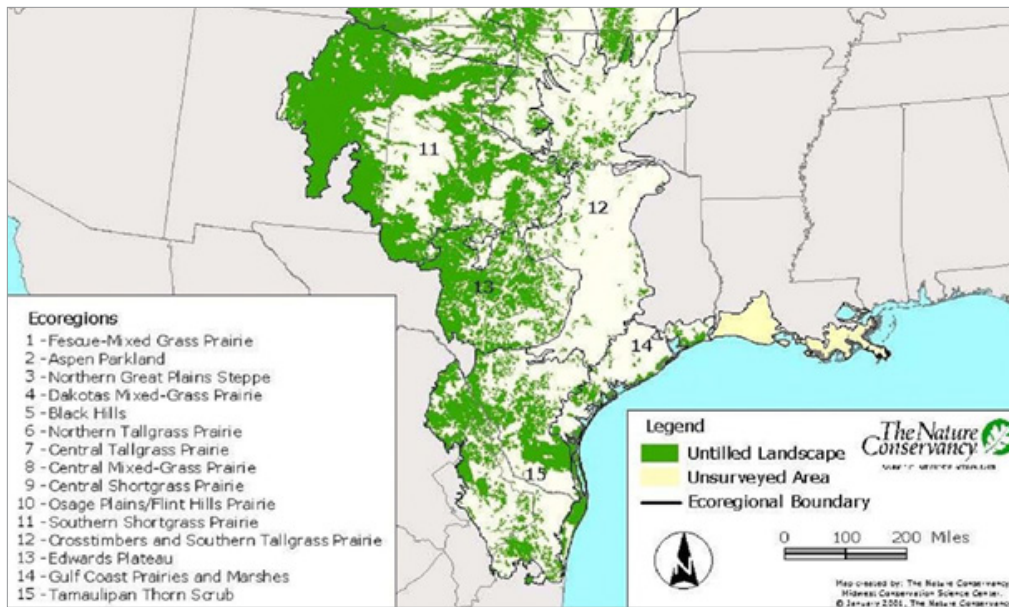


Figure 8.3. Untiled lands in Oklahoma, New Mexico, and Texas. *Courtesy of the Nature Conservancy.*

Economically, the impact is substantial. In 2001 alone, the estimated annual losses due to catastrophic wildfires, reduced cattle forage, diminished wildlife habitat, decreased recreational opportunities, and lower water yields amounted to approximately \$218 million¹².

Reduced Soil Health

Much of Oklahoma has been previously tilled (**Figure 8.3**). This previously cropped land has been converted to or reverted back to grassland. This land typically has lower productivity (approximately half) and greater erosion than grasslands never cropped. This is due to a large extent to the loss of soil organic matter during the initial years after breaking the land out (50% of soil carbon lost in first 5 years of initiating cropping)^{13,14,15,16} and loss of soil fertility which may take decades or even centuries to restore. Soil organic matter is a key attribute of soil quality and impacts water infiltration.

Burke et al (1995)¹⁷ found that restoration of soil N required 50 years after reintroduction of native perennial grasses. Kindscher & Tieszen (1998)¹⁸ found that even 35 years after restoration of tallgrass prairie on a previously cultivated site, soil organic matter remained lower than native prairie. Fuhlendorf et al. (2002)¹⁹ found that soil carbon, total nitrogen, organic matter, nitrate, and potassium were significantly lower

and percent bare ground higher in grasslands previously cultivated and restored. Soil nitrogen and soil carbon on these previously cultivated mixed prairie sites were 30–40% lower than native prairies, while bare ground was 40% higher.

Heavy grazing can further impact and prolong restoration by increasing carbon allocation to leaves, reducing litter accumulation, increasing bare ground, decreasing root biomass, and ultimately lowering nutrient inputs into the soil. On previously cultivated sites, soil nitrogen and carbon were higher with moderate grazing than with heavy grazing. In comparison, grazing minimally impacted soil nutrients on native sites. This suggests that greatest benefit of grazing management to soil fertility and health should be realized on previously cultivated grasslands.

Key Science Advancements/ Proposed Solutions to Reduced Water Availability

The working group identified eight potential solutions to the problems of eastern redcedar encroachment, reduced soil health, and reduced water availability related to weather and climate. These solutions are discussed in the sections that

follow. Each solution was researched, resulting in significant scientific advancements.

Eastern Redcedar (ERC) Encroachment

The working group proposed several solutions to address eastern redcedar encroachment:

- Support continued funding and expansion of programs to remove harmful woody species (i.e., the Terry Peach North Canadian Watershed Restoration Act and Terry Peach Watershed Restoration Act) by **quantifying how restored native prairie improves water availability** using targeted monitoring and improved modeling
- Support planning and control efforts **using satellite imagery to monitor ERC** presence across Oklahoma
- **Understand and quantify social acceptance, adoption barriers, and public willingness to enhance ERC removal** programs, particularly using controlled burns for smaller trees

To support continued and expanded funding for removing harmful woody species in watersheds, decision makers need data on its benefits. S3OK research highlights that restoring native prairie by mechanically removing encroached juniper significantly improves water availability through increased root zone soil moisture and watershed runoff. Using a paired watershed approach, we observed that soil water storage

in the top 1-meter profile doubled, and annual runoff increased by more than fourfold following restoration. Ongoing monitoring of soil moisture and runoff dynamics across various phases of restoration provides valuable empirical data to refine hydrological models and enhance predictions of water availability under different land-use scenarios²⁰. Conversely, S3OK modeling assessed the impacts of doing nothing and not controlling ERC. Yang et al. (2024)²¹ found that if all grasslands in Little River Watershed were allowed to convert to forests, it would lead to a 41% reduction in streamflow.

ERC management efforts require accurate monitoring of ERC presence. Our study shows the potential of using satellite-based remote sensing to measure, monitor, report, and verify the spatial-temporal dynamics of eastern redcedar trees and forests in Oklahoma and the Southern Great Plains at high spatial resolution (30-m) and annual temporal resolution²² (Yang et al., 2023). The resultant annual maps of eastern redcedar forests can assist agencies in monitoring management efforts and areas experiencing continued expansion, and support stakeholders' communication and decision on the removal and/or control of eastern redcedar trees/forests. Yao et al. (2025)²³ showed that expansion is not uniform across the state (**Figure 8.4**). Most expansion is occurring in the eastern half of the state, filling in areas among existing forests.

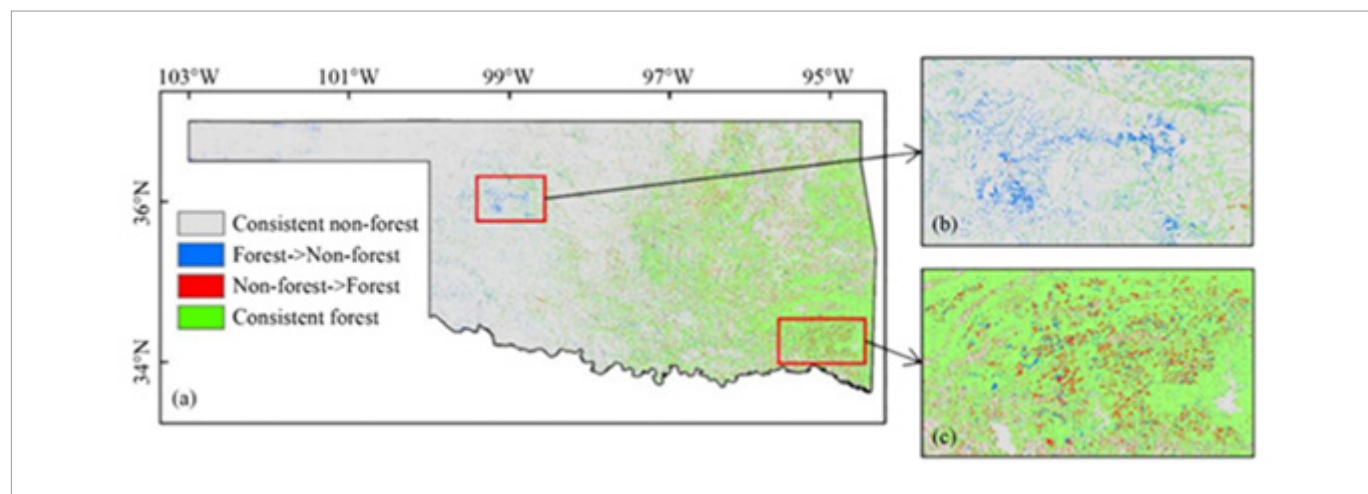


Figure 8.4. Spatial distribution of forest cover changes for Oklahoma from 2016–2020 (from Yao et al., 2025).

Our study also shows the potential of using satellite-based models, which estimate gross primary production (GPP) and evapotranspiration (ET), to assess the impacts of woody plant encroachment on the carbon fluxes and water fluxes (Yang et al., 2024). The resultant GPP and ET data products can also be used to support stakeholders' communication and discussion on the ecological and environmental effects of woody plant encroachment.

Finally, our study indicates that public willingness to support Eastern Redcedar (ERC) removal programs using controlled burns is influenced by several social and demographic factors. While rural residents are more knowledgeable about ERC encroachment and its risks, both rural and non-rural residents express concerns about wildfire hazards. Controlled burns are recognized as effective management tools, but liability and safety concerns are major barriers to their acceptance.

Results suggest that residents who have experienced prolonged droughts or expressed concern about water availability are more likely to support prescribed fire as a management practice. However, non-rural residents, particularly those living in areas with a high wildland-urban interface (WUI), are less familiar with controlled burning practices and may need targeted educational outreach to increase their support. Public-private partnerships and community-based fire management programs could help address liability concerns and improve public acceptance of prescribed fire²⁴. Further, a statewide study to identify areas of lowest risk for prescribed fire could be helpful for targeting areas for prescribed burning and related outreach efforts, as well as areas of high risk which should be targeted for mechanical control.

Reduced Soil Health

The working group recognized the need for improved soil health across all land uses in Oklahoma, particularly on grazinglands (rangeland and pastureland) and cropland. Ongoing USDA funded projects are evaluating

the benefits of soil health practices to cropland. Thus, S3OK and the working group focused on identifying solutions to the problem of reduced soil health in rangeland and pastureland systems (the largest land use in Oklahoma).

The solution evaluated was: **implementing regenerative livestock grazing** to improve soil water infiltration, as well as drought resiliency and soil health. S3OK research compared two grazing management systems, adaptive and prescriptive, to determine the best method for improving soil health and overall sustainability. Regenerative livestock grazing is a management practice designed to sustain grassland ecosystems and soil health. This approach emphasizes balancing grazing pressure with adequate vegetation recovery periods, ensuring the continuous presence of living root systems in the soil. Such practices promote the sustained growth of soil microbial communities, leading to increased soil organic matter content.

Consequently, improvements in soil structure, aggregation, and porosity are anticipated, resulting in enhanced water-holding capacity and infiltration rates, providing resilience to drought and flooding. When combined with increased plant diversity, this practice extends the growing season, boosts producers' income, and enhances ecosystem services such as carbon sequestration and wildlife habitat improvement.

Our study in rotationally grazed pastures in southern Oklahoma revealed a positive correlation between the dominance of oligotrophic microorganisms and soil organic matter content. This finding suggests that under proper grazing management, the addition of fertilizers may not be necessary for maintaining soil health (manuscript in preparation).

We also observed a decrease in soil microbial biomass and respiration immediately following grazing events, attributed to the reduction in aboveground plant biomass. However, after two years of rotational grazing, these microbial indicators consistently increased, demonstrating

the long-term benefits of this management approach (manuscript in preparation).

Finally, our work emphasized the importance of aligning grazing intensity and frequency with the soil's nutritional characteristics. In grasslands relatively deficient in organic nitrogen, higher grazing frequencies (e.g., nine grazing events over two years, with at least 60-day resting periods) positively influenced microbial biomass compared to lower frequencies (e.g., four grazing events over two years) (manuscript in preparation).

Produced Water Treatment, Resource Extraction, and Reuse

To better meet long-term oilfield and agricultural water needs and create potential for year-round production, potential solutions identified include:

- **Microbial pre-treatment** to remove hydrocarbons
- Improving **oil-produced water separation** techniques
- Pilot testing and further development of cleaning produced water **using membrane distillation to remove salinity** and making it available for irrigation
- Develop and enhance **new techniques for resource extraction**
- Evaluate **carbonated produced water** for enhanced oil recovery

Microbial Pretreatment to Remove Hydrocarbon

Economically removing dissolved hydrocarbons from produced water is challenging but ultimately necessary for any land-application reuse of the water. Bioremediation (using microbes to degrade contaminants) is often used in soils, sediments, and groundwater as an effective, sustainable, socially acceptable, and safe means of destroying toxic compounds from spills, leaks, and other contamination sources. There have been extensive research and application showing degradation of hydrocarbons by microorganisms in freshwater, soils and low-salt environments^{25,26,27}. PWs are,

however, very salty, far beyond the salt-tolerance limits of those bacteria.

Recent studies have shown the ability of salt-loving (halophilic) and salt-tolerant (halotolerant) organisms to degrade hydrocarbons at salinity ranging up to 30% salt^{28,29} suggesting their potential application in bioremediation of PW. We have enriched several hydrocarbon-degrading microbial cultures from various locations including oil-contaminated sediment from Rozel Point at Great Salt Lake (UT), crude-oil-contaminated soil (Kuwait), soil from Salt flat (OK), and an oil production facility in Seminole County (OK)^{30,31}. These enrichment cultures are robust and capable of degrading a mixture of petroleum compounds at high salinity.

Recently, we successfully isolated a salt-loving (halophilic) bacterium, *Modicisalibacter* sp. strain Wilcox from the First Wilcox formation in Payne County. This bacterium degrades a variety of petroleum compounds in the presence of salt up to 24%³². In addition, strain Wilcox can withstand high levels of heavy metals that are typically found in PW. Furthermore, the strain has the ability to remove some of the toxic heavy metals such as Mn, Zn, Se, Pb, Cu, and Cr by biosorption and bioaccumulation mechanisms. Also, the bacterium has the capacity to recover 98% of 2 mM lanthanum present in the medium through a combination of biosorption and bioaccumulation mechanisms. This ability is particularly significant for resource recovery from PW (discussed later), offering a sustainable approach to extracting valuable elements from wastewater. Overall, this bacterium holds significant promise for the development of a sustainable bioremediation process for the removal of toxic hydrocarbons and heavy metals in PW-fed bioreactors. However, this technology is not pilot-scale ready because of the growth rates, settling time, and robustness to changing water chemistries, the 'completeness' of the hydrocarbon removal still needs to be tested.

Improving Pre-Treatment Oil-PW Separation Techniques

Our work sought to gain a deeper understanding of the interface and its related properties in produced water and oil systems. The interfacial dynamics between oil and water play a pivotal role in the efficiency of separation processes within the oil and gas industry, particularly in the management of PW, which is a complex aqueous byproduct of hydrocarbon extraction enriched with salts, hydrocarbons, and dissolved ions. We investigated the intricate interplay between interfacial viscoelastic properties and emulsion behavior, focusing on optimizing separation techniques. Using synthetic PW and cyclohexane systems as a model, we analyzed the interfacial tension and dilatational viscoelasticity under varying surfactant (sodium dodecyl sulfate, SDS) concentrations.

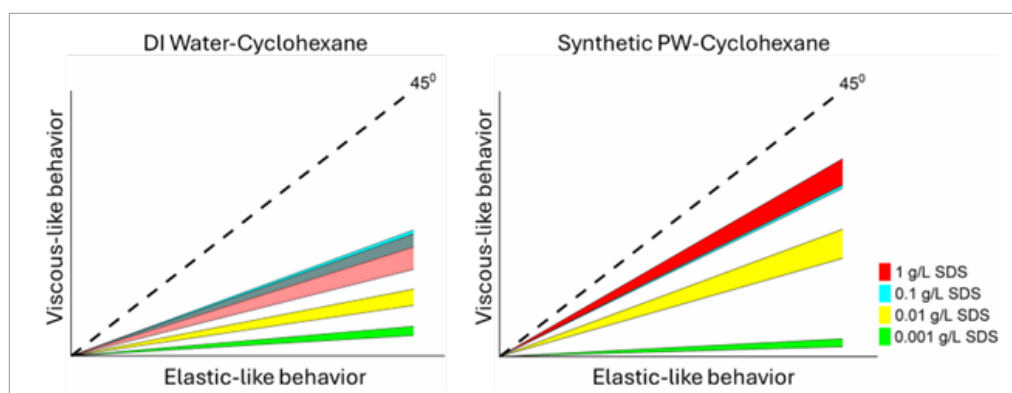
The experimental approach involved synthesizing PW based on established compositions and pairing it with cyclohexane, a representative hydrocarbon phase. Interfacial tension measurements revealed a significant divergence from pure water–cyclohexane systems. Notably, the baseline interfacial tension for PW–cyclohexane was found to be 44.47 ± 0.32 mN/m—approximately 4.5 mN/m lower than the 47.94 ± 1.26 mN/m observed in pure water–cyclohexane systems. This reduction highlights the complex ionic composition of PW, which significantly enhances surfactant activity.

The interfacial tension and dilatational viscoelastic properties were examined through a systematic

analysis of sodium dodecyl sulfate (SDS) concentrations. Key findings indicate that the critical micelle concentration (CMC) for SDS in the PW–cyclohexane system is 0.1 g/L, markedly lower than the 1.8 g/L observed in water–cyclohexane systems. Dynamic dilatational studies further revealed that at optimal SDS concentrations (0.01 g/L for PW and 0.1 g/L for water), interfacial moduli peaked, signifying a balance between elastic and viscous responses essential for emulsion stabilization or destabilization. Furthermore, as illustrated in **Figure 8.5**, the phase angle steadily increases with SDS content in both systems, and a change toward more viscous–dominant behavior at the interface is observed. However, the interfacial behavior in PW systems shifted more rapidly, underscoring the unique impact of PW's ionic complexity.

Further insights were derived from dilatational rheology analyses conducted at oscillatory frequencies ranging from 0.1 to 0.5 Hz. These experiments quantified the viscoelastic response of the interface through the storage modulus (E' , elastic component), loss modulus (E'' , viscous component), and complex modulus (E^*). In pure water–cyclohexane systems, peak moduli occurred at an SDS concentration of 0.1 g/L, reflecting an optimal balance of elasticity and viscosity. Conversely, in PW–cyclohexane systems, the maximum moduli shifted to 0.01 g/L, with a notable increase in the phase angle—indicative of a transition toward viscous–dominated behavior. This shift, accentuated in PW, suggests that ionic interactions accelerate surfactant saturation at the interface, limiting dynamic molecular rearrangement and reducing elasticity at higher concentrations.

Figure 8.5. Variation in phase angle: each region represents the range of minimum and maximum phase angle values recorded for the solutions at frequencies between 0.1 and 0.5 Hz.



These findings have significant implications for improving separation processes in oilfield operations, where stable oil-in-water emulsions impede efficient phase disengagement. The lower CMC and altered viscoelastic profile in PW-cyclohexane systems indicate that minimal surfactant dosages can destabilize emulsions, facilitating oil-water separation with reduced chemical input. This enhanced sensitivity to SDS in PW highlights the critical role of water chemistry in interfacial dynamics, offering a strategic framework for tailoring surfactant applications in enhanced oil recovery, wastewater treatment, and emulsion management.

By bridging fundamental interfacial science with practical applications, this research provides a robust foundation for advancing separation technologies. Future investigations will explore additional surfactants and environmental variables, such as temperature and pressure, to further refine these interfacial systems, aligning with the industry's pursuit of efficiency and sustainability.

Membrane Distillation (MD)

MD is a promising “next-generation” desalination technology that is still being developed for commercial uses. One unique advantage of MD over other membrane systems is its ability to recover water from practically any salinity level. The unique advantage of MD over systems like conventional reverse osmosis is that energy input into the system is heat, which can come from a variety of sources. Many oil fields do not possess the infrastructure to capture natural gas co-produced with petroleum. These fields produce waste heat when the natural gas is flared. In addition to flare gas, solar thermal technologies, heat produced from ‘stranded electrons’ in wind-producing areas, heat from compressors and pumps in the oil field, and natural geothermal heat associated with oil production wells are all options at several sites. After successful development in the laboratory scale system proposed herein, our prototype will be piloted at a deep well injection site with high solar radiance, contains active oil production wells producing waters

with high geothermal temperatures ($\sim 60^{\circ}\text{C}$), and is within a wind turbine field (with the major transmission station within a quarter mile of the site). This provides many promising options for providing the energy needed to drive a full-scale operation system.

We have made significant progress in investigating MD systems for PW treatment. In our work to date, we have used MD to treat PW from six formations in Oklahoma, Colorado, and Texas. We achieved 60–86% water recovery in this raw PW, which ranged from 20,800–154,000 mg/L total dissolved solids (TDS), proving that the process can desalinate at practically any salinity; however, we found that crystallization of the inflow should be avoided to avoid membrane fouling from salt crystallization. In this process, we also increased the concentrations of valuable elements [e.g., lithium (Li), iodine (I), bromine (Br), and manganese (Mn)] in the supersaturated brine. For example, we increased Li concentrations in one PW from 8.9 mg/L to 52.5 mg/L. Further, valuable rare earth elements (e.g. lanthanum, neodymium, and europium) have been found to be present in salt crystals generated from the brine concentrate. We have also tested raw incoming waters to D&B’s facility and waters after their gravity separation process. We found that even the existing crude pretreatment step onsite leads to drastic improvement of membrane quality and performance. This demonstrates the importance of a unit-operations design that removes organics prior to desalination.

Resource Extraction Using Modified Silica Particles

A major advancement was made through S3OK in resource extraction technology, especially for recovering rare earth elements (REEs) such as lanthanum (La^{3+}). We focused on La^{3+} due to its significant value in the electronics industry. REEs are crucial for producing renewable energy technologies, sophisticated electronics, and essential infrastructure materials. However, their extraction has often been inefficient and harmful to the environment. Our research centers on utilizing chemically modified silica particles for

the selective and efficient recovery of lanthanum. By modifying the surface chemistry of silica particles with Pr-EDTriA groups in alkaline conditions, we significantly enhanced their ability to bind La^{3+} specifically. At an optimal pH of 11.3, these particles showed improved stability and functionality, validated by thermal gravimetric analysis (TGA) and zeta potential measurements.

A particularly exciting feature of this research is the remarkable selectivity of modified silica particles in challenging saline environments. Many industrial waste streams, such as those from produced water treatment, often have competing ions like Na^+ that can disrupt traditional recovery techniques. Our experiments showed that the modified silica particles achieved a La^{3+} recovery rate exceeding 98 wt.%, even in the presence of Na^+ ions (100 ppm) (**Figure 8.6**). This result motivates our future work that focuses on utilizing more selective ligands to remove La^{3+} at higher salt concentrations. By customizing the surface characteristics of silica particles, this technology enhances extraction efficiency, decreases energy use, and minimizes chemical waste, making it an attractive option for industrial use.

The kinetic improvements achieved by modifying silica particles represent a significant advancement in the recovery of La^{3+} ions from aqueous solutions. Our experiments showed that unmodified silica particles took 20 hours to reach

equilibrium, while the modified silica particles, optimized at pH 11.3, reached maximum recovery in just 2 hours—a tenfold boost in adsorption speed. This notable enhancement is further underscored by the modified particles' ability to resist the negative effects of Na^+ ions, which slowed the sorption rates for unmodified silica but did not affect the performance of the modified particles. The faster kinetics are due to the improved surface chemistry of the modified silica particles; the introduction of TMS-EDTriA groups enhanced binding strength through multivalent interactions and uncovered additional active sites for adsorption (**Figure 8.7**). Furthermore, the more negative zeta potential at pH 11.3 has heightened the electrostatic attraction between La^{3+} ions and the particle surface, promoting quick and effective binding. This advancement in kinetics leads to increased throughput in practical applications, significantly decreasing processing times and enhancing the feasibility of selective ion recovery from complex aqueous systems.

We have successfully refined and validated this technology by incorporating characterization techniques like thermal gravimetric analysis (TGA) and scanning electron microscopy (SEM), ensuring it remains reliable under various operating conditions. These innovations open up possibilities for sustainably recovering essential materials from waste streams, aiding in reducing dependence on imports and traditional mining practices for

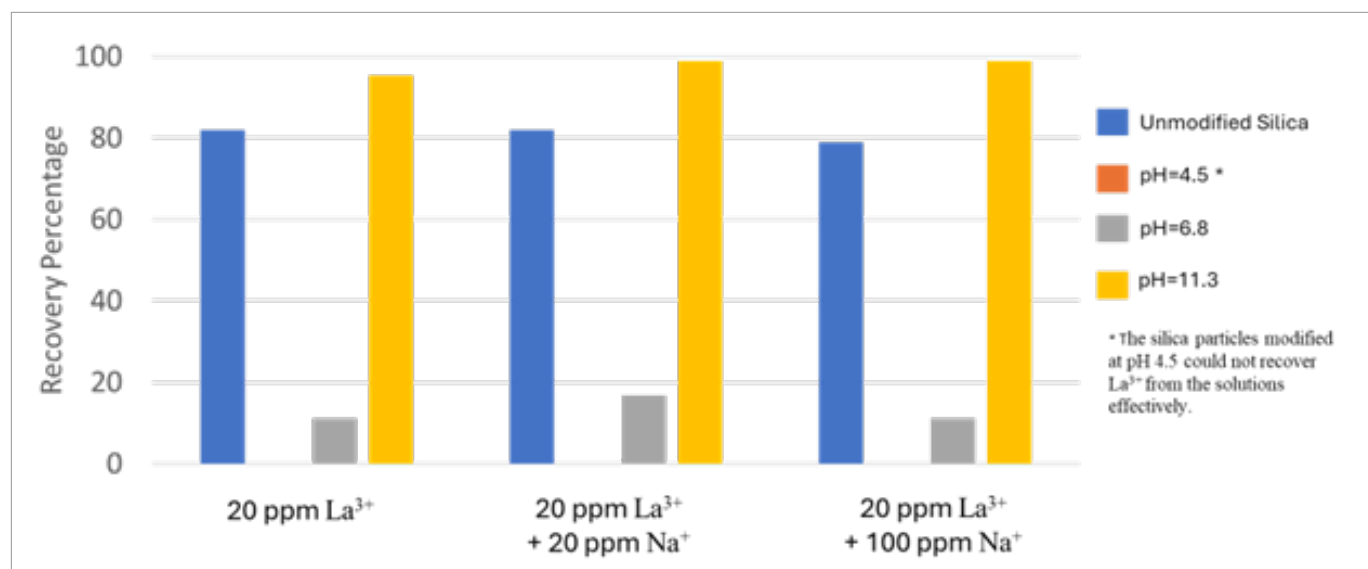


Figure 8.6. La^{3+} recovery after 24 hours of mixing.

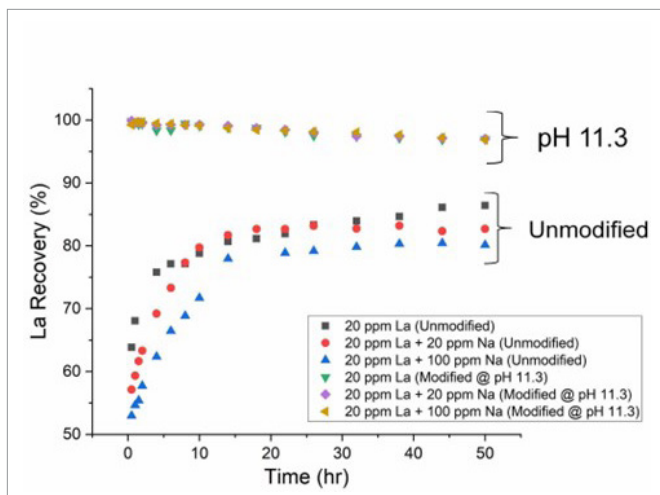


Figure 8.7. La^{3+} recovery percentage over time for unmodified and modified silica particles at pH 11.3 in different solutions.

lanthanum while also meeting the increasing global demand for clean energy and advanced technologies.

Carbonated Produced Water for Enhanced Oil Recovery

Members of the working group also investigated the potential of high salinity carbonated water flooding (HS-CWF) for enhanced oil recovery (EOR), CO_2 storage, and produced water disposal using microfluidics and conventional coreflooding experiments. They demonstrated that CO_2 solubility in the brines increases significantly with pressure from 150 to 1000 pounds per square inch gauge (psig), with minimal changes observed between 1000 and 1200 psig. Experimental results aligned well with established thermodynamic model predictions, and a new correlation was developed linking CO_2 solubility to brine density at ambient conditions.

In hydrocarbons, both CO_2 solubility and the swelling factor increased with pressure (150–700 psig), while the swelling factor decreased with increasing hydrocarbon molecular weight. Interfacial tension (IFT) measurements revealed a linear decrease in IFT with increasing pressure across all the salinities tested and a linear increase with brine salinity across the pressures tested. Microfluidic experiments showed pressure-dependent EOR performance, with greater reductions in residual oil saturation observed at

700 psig compared to 150 psig across the oil-water systems studied. Coreflooding experiments indicated that low-salinity waterflooding (LSWF) and carbonated waterflooding (LS-CWF) were more effective for oil recovery compared to high-salinity waterflooding (HSWF) and carbonated waterflooding (HS-CWF), respectively, and Bentheimer sandstone cores exhibited superior performance over Berea sandstone cores under identical test conditions. CO_2 sequestration potential also varied with salinity and pressure: high-salinity CWF performed better at 700 psig, whereas low-salinity CWF was more effective at 150 psig.

This multi-scale experimental approach demonstrates the complex interplay between pressure, salinity, oil type, and rock type in determining the effectiveness of carbonated produced water flooding for EOR, CO_2 storage, and produced water disposal. Findings support the use of CWF as a viable low-carbon EOR strategy, particularly under high-pressure conditions and with optimal brine salinity.

Annotated Treatment Train for Produced Water

The work group produced a vision for a produced water treatment system that is:

- Flexible to handle variant water chemistries found in PWs and similar oily briny groundwater formations,
- Reliant on low-grade energy sources (heat) as the primary desalination mechanism to allow for flexibility around site-specific economic considerations of available energy resources (i.e., site specific geothermal, solar, electric, industrial, and waste heat resources),
- Scalable to the current and future water reuse needs and influent water availabilities at a given site (i.e., the system can upscale or downscale without significant site-specific capital investment) and
- Incorporates considerations for add-on processes for simultaneous water recovery and elemental recovery goals (Elemental

recovery operations taken off of side streams, when feasible, have the potential of creating net value more than offsetting any cost of treatment; similarly, microbes can at times sorb certain heavy metals of economic interest).

The overall schematic of the current vision is provided in **Figure 8.8**.

Currently, step 1 (pretreatment processes to capture recoverable oil) is ready for pilot-scale testing. For the second step (biological degradation of organics and membrane distillation), work in the laboratory is still needed to determine appropriate scales and robustness during continuous flow operations of the processes (~1–2 years of work). For step 3 (elemental recovery processes), data on Lanthanum recovery is encouraging enough to field test the ability to capture the metal on modified silica nanoparticle membranes and from the microbial sorption; however, Lithium, Iodine, and other metal recoveries still need development in the lab (~2–3 years of development and testing). Our goal is that with sufficient financial resources

to proceed with laboratory-scale development, in 3 years, a fully built-out pilot plant with integrated water and metal recovery will be tested in the field. As we progress with the pilot scale evaluation, we will:

- Evaluate how useful resource extraction can be from a geopolitical and economic standpoint; and
- Identify/delineate optimum conditions for implementation and potential limitations.

Future Work/Considerations

Continued work is needed to improve soil health, including expanded support for state (Oklahoma Conservation Commission) and federal cost share and technical support programs (USDA Natural Resource Conservation Service). Research is needed to better understand the effects of soil health practices, particularly in semi-arid environments (western Oklahoma) and grazinglands. In particular, a better understanding of the impacts of soil health practices on farm/ranch economics, soil nutrient

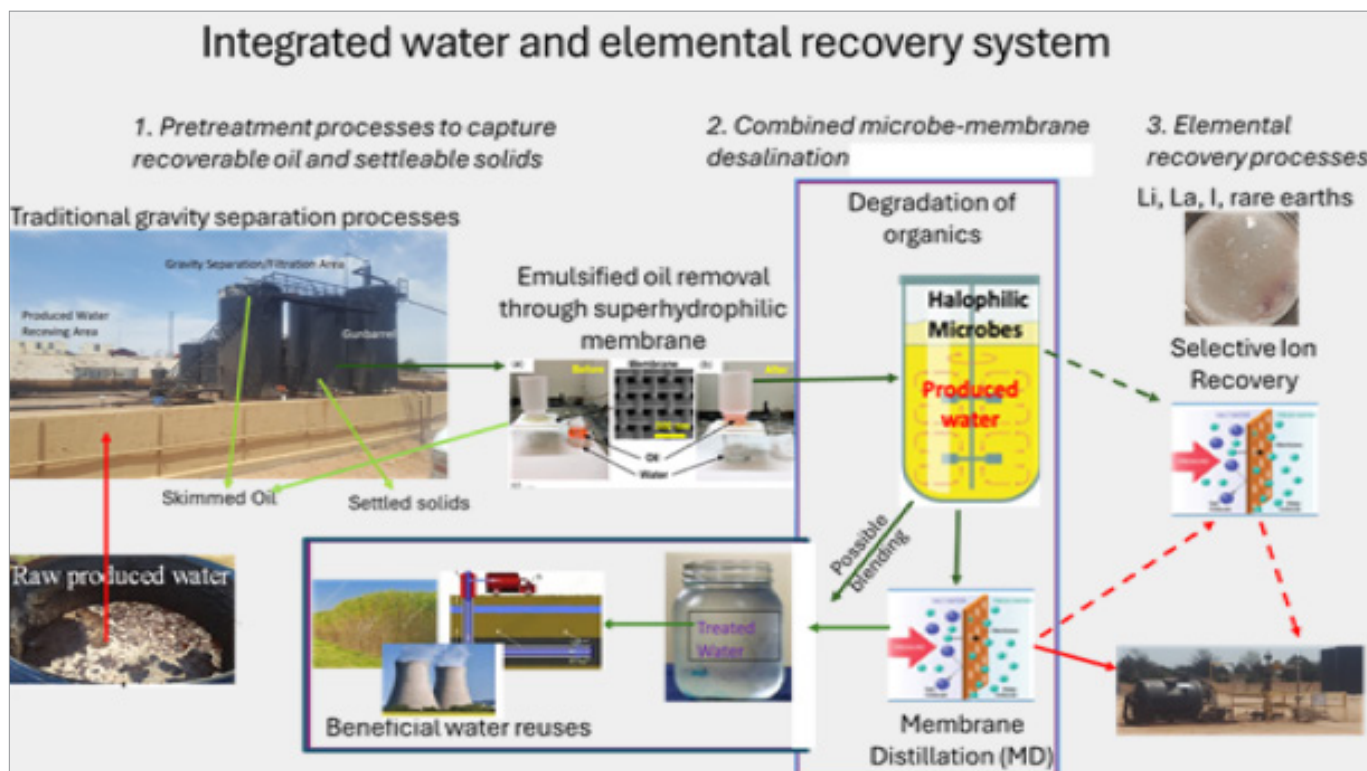


Figure 8.8. Produced Water Treatment train.

cycling and availability, agricultural production/yields, water resources, and other ecosystem benefits is needed. Additionally, effects of soil health practices on grazinglands and their ability to restore degraded sites, particularly those previously cropped, is needed. Finally, a better understanding of barriers to adoption and incentive structures is needed in order to develop and implement appropriate programs to encourage adoption.

Similarly, expanded efforts are needed to manage eastern redcedar and halt its expansion. An improved understanding of the ecosystem, grazing, and economic impacts of ERC control is needed, appropriate incentives, and barriers to adoption are required. Incentive programs are certainly needed to encourage control efforts statewide (i.e., passage of the Terry Peach Watershed Restoration Act), along with outreach and an identification of areas most suitable for prescribed fire versus mechanical controls.

With PW treatment and reuse, our goal is to make demonstrable progress towards implementation of a small-scale pilot treatment opportunity for produced water reuse, and lay the groundwork for a five-year time horizon implementation guide that underscores future regulatory considerations, resource recovery opportunities, potential for agricultural use, and reduced treatment costs, new economic opportunities, and enhanced environmental benefits. Authorization of an Oklahoma Produced Water Consortium is proposed to enhance development and adoption of PW treatment and reuse.

Current Regulatory Environment for PW Reuse in Oklahoma

The Oklahoma Corporation Commission Oil and Gas Division regulates oil and gas development, including the management of PW. In 2020 the **Oil and Gas Produced Water and Waste Recycling and Reuse Act** was enacted to support the reuse and recycling of PW. This law grants operators and non-operators the right to manage, transfer, sell, or treat PW, giving them exclusive rights to any resulting proceeds. Ownership of PW is retained

by the operator until transferred, at which point it becomes the property of the new handler. The bill also protects entities that recycle and transport PW from liability, encouraging the transformation of PW from a waste product into an economically valuable resource. Additionally, changes to drilling permits and injection well applications were introduced, including stricter requirements for well integrity, elimination of the Area of Review (AOR) requirement for gravity flow injections, and the need for radioactive tracer surveys to ensure mechanical integrity in simultaneous injection operations.

This regulatory framework provides a good foundation for future use. However, as PW treatment and reuse progresses, additional work will be needed by agencies, industry, and university partners to **identify and help implement needed policies and regulations to support the proper use of produced water.**

Resource Recovery Potential

Produced water (PW) can include valuable elements such as lithium, magnesium, barium, strontium, boron, bromine, iodine, zinc, and other rare earth elements (REEs). These components are regarded as vital minerals essential for advancing clean energy technologies and various industries^{33,34}, indicating PW's potential as a source for their recovery. In addition, recovering these minerals from PW can have serious national security ramifications. Since several of the elements in PW are used in defense technology and vital sectors, the US government has designated them as "critical minerals," indicating that disruptions in their supply chain might majorly affect national security. Since almost all REEs are now imported into the United States, there is much interest in locating alternate domestic sources of these elements³⁵. Additionally, as per the report by the US Department of Commerce³⁶, the United States is highly dependent on foreign nations, such as China, to supply critical minerals. Over-reliance on foreign countries and foreign sources for essential minerals and materials presents serious national and economic security risks.

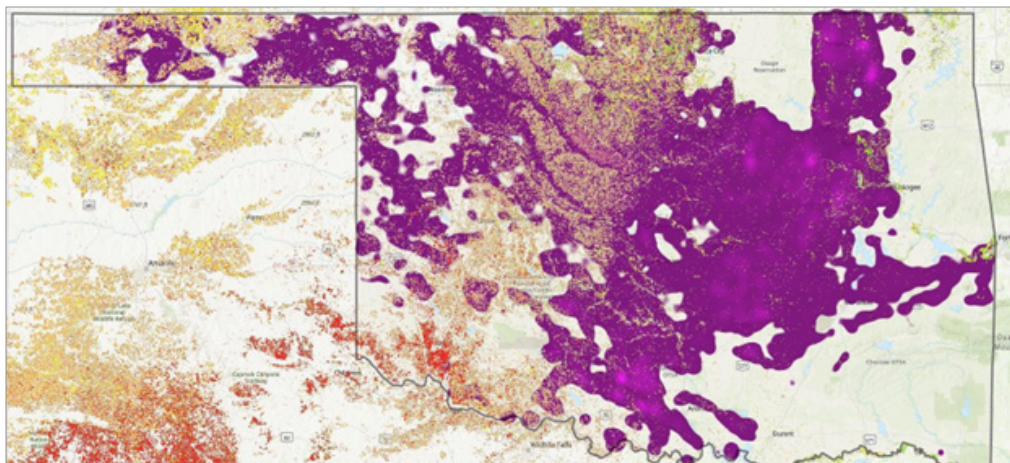


Figure 8.9. Locations of Oklahoma and Texas Panhandle cropland (granular dots) and oil and gas wells (purple heat mapping).

The amount of PW produced in the U.S. has been increasing, as has the demand for its management or recycling. When valuable components are extracted from it, what was once thought of as a waste product from the production of oil and gas is transformed into a potential resource necessary for clean energy technologies while reducing the environmental impact of disposing of large amounts of PW³⁷. During oil and gas production in the U.S., almost 2.8 billion gallons of PW were produced daily in 2017³⁸, which rose to almost 3.0 billion gallons daily in 2021³⁹. Resource extraction from PW would give the country a domestic supply of vital minerals like lithium and rare earth elements (REEs), lessen import dependency, generate new employment in the processing and treatment industries, cut disposal costs for oil and gas companies, and boost clean energy technology by supplying vital components.

Potential Agricultural Use of Treated PW

Treated PW presents a potential, though complex, opportunity for agricultural use, especially in water-scarce regions like western Oklahoma. Oklahoma produces approximately 1.5 billion barrels of produced water annually, equivalent to 487,650 acre-feet—a volume theoretically capable of supporting over 200,000 acres of high water-demand crops, assuming a 2-foot-per-acre annual water requirement. However, several factors limit the direct application of this resource.

Treated PW has potential uses in the irrigation of non-food crops, tree plantations, and landscape

projects. However, its use requires careful management to ensure water quality meets the necessary standards to avoid negative impacts on soil health and crop productivity. Identifying optimal treatment methods and appropriate agricultural applications is essential for maximizing the benefits of produced water while minimizing risks.

A primary challenge is the spatiotemporal mismatch between PW availability and agricultural demand. Transporting produced water long distances for agricultural production is generally cost-prohibitive. This limits its application to areas near treatment facilities. Fortunately, much of Oklahoma's cropland sits comfortably in areas dense with oil and gas wells (**Figure 8.9**).

Another challenge of PW use for agricultural production is the temporal differences in PW production and crop needs. While produced water generation is relatively constant, agricultural water needs, particularly for crops, are concentrated during specific growing seasons (typically spring and summer). This seasonality makes consistent, year-round utilization difficult. Even with high water-use crop rotations, periods of low demand will exist while treatment facilities operate continuously.

Despite these challenges, certain agricultural applications in western Oklahoma show promise. Cotton production, both favored by the region's land use history but limited by water availability in the region's dry climate, offers a viable option because of its wide planting, high water needs

and potential to be co-located with potential produced water facilities. Similarly, turf grass and bioenergy crops could be considered. Rangeland restoration and localized irrigation of alfalfa or pasture near produced water facilities are also possibilities, though the latter requires careful consideration of potential impacts on the food chain. Soil productivity near treatment facilities also plays a role. In some areas, like the Permian Basin, soils may require substantial investment to become suitable for irrigated cropland.

A potential solution to the mismatch in time might be solved in a hybrid mode of agriculture use induced artificial recharge of aquifers. That is—locating treatment plants near alluvial aquifers, using grasslands or other agriculture use for final filtration and allowing excess treated produced water to percolate into the aquifer, providing long-term storage and a means of distributing water when needed. This approach requires further investigation to determine its logistical and environmental impact.

In conclusion, while the sheer volume of PW in Oklahoma suggests a significant potential resource for agriculture, the spatiotemporal mismatch between supply and demand, coupled with transport limitations and soil conditions, necessitates innovative approaches. Artificial aquifer recharge and carefully selected crop applications, such as cotton, offer promising avenues for further exploration.

Finally, careful consideration of water quality, treatment methods, and the specific agricultural context is essential to ensure the sustainable use of produced water in agriculture. Further research is needed to address knowledge gaps and develop guidelines for its safe and efficient application including:

- What types of non-food crops (e.g., bioenergy crops or fiber crops) can be effectively irrigated with treated produced water, and how does salinity impact their growth and productivity?
- How can treated produced water be integrated into reforestation and erosion

control efforts, such as tree nurseries, shelterbelts, and riparian buffer zones?

- What are the potential benefits and risks of using treated produced water for landscape irrigation in highway and municipal projects, particularly regarding soil health and water conservation?
- What are the necessary treatment processes to ensure that produced water is safe and sustainable for agricultural use, and how do these vary across different crop types and soil conditions?

Improved Treatment Cost, Economic Opportunities, and Environmental Benefit

Treatment cost for produced water varies depending on the characteristics of the produced water, treatment technology, and purpose of reuse⁴⁰. Capital investment for treatment plants and pipeline infrastructure is high. Newfield Exploration, a PW treatment company located in Oklahoma, estimated that the capital cost of a piping and treatment network was approximately \$90 million. Newfield's treatment cost for produced water was estimated at \$1.26/m³ (\$0.20/bbl). The treatment costs could range from \$0.09/m³ to \$12/m³ to use produced water for irrigation⁴¹.

There are also potential revenue streams to offset some of the treatment costs, such as extracting valuable minerals or chemicals from produced water and selling the treated water to be used in agriculture or other industries⁴². For example, Eureka Resources, a company in Pennsylvania, recovers marketable byproducts during treatment, such as methanol, sodium chloride, and calcium chloride⁴³. Methanol is an organic chemical compound that can be used as a solvent, fuel, and pesticide. Its [global market price ranges from \\$346–\\$372](#) per ton in 2025. Sodium chloride (NaCl) can be used for road deicing. The global market for this chemical was valued at \$18.97 billion in 2023 and is [projected to reach \\$25.37 billion by 2032](#). Calcium chloride (CaCl) can be used as drilling fluids in addition to deicing, construction, and pharmaceuticals. The U.S. is the

world's largest importer of CaCl. In 2022, the US imported almost \$73 million of these compounds. The global CaCl market size was valued at \$1.7 billion in 2023 and is [projected to be \\$2.3 billion in 2030](#). Research in Kern County of California has shown that diluted low-saline produced water for irrigation is of comparable quality to the local groundwater in the region⁴⁴. This could be a potential revenue stream for treatment plants, especially during drought years.

In Oklahoma, limiting reinjection of produced water could mitigate environmental damage, especially the induced seismic events. Induced seismic events in Oklahoma have negative impact on Oil & Gas industry's infrastructure as well as residential property values⁴⁵. FEMA (2023)⁴⁶ estimates the annualized earthquake loss (AEL) in Oklahoma is 24 million \$ and ranked 27 in the nation. AEL provides a long-term average of expected annual damages.

PW Consortium/Regional Efforts

To hasten advancement of PW treatment and use, a coordinated effort will be needed. An Oklahoma Produced Water Consortium is proposed to support this cause and help advance research, development, and piloting PW treatment and resource recovery. The S3OK Produced Water Research Team already joined the New Mexico Produced Water Research Consortium in early 2025 to enhance collaborative opportunities with researchers and industry from surrounding oil-producing states. Through participation in this consortium, we have begun meeting monthly with leaders of the Texas-, New Mexico-, Colorado-, and Wyoming-produced water consortiums. These collaborations are expected to yield new opportunities for joint research, enhanced resources for technology development, elimination of duplication of effort, and increased speed of development and deployment of new treatment technologies and, ultimately, reuse of produced water.

Members of the S3OK Produced Water Research Team are discussing with university administrators, agency partners and industry,

the possibility of formally forming an Oklahoma Produced Water Research Consortium. Through formal formation of consortiums in New Mexico, Texas, and Colorado, state and federal resources have been secured by these states to enhance needed research, testing, and policy development. We would strive for a similar outcome to advance produced water treatment and reuse in Oklahoma to support agricultural and industrial (O&G) needs while supporting new industries (resource recovery, treatment technology, etc.).

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CHAPTER 9

Socially Sustainable Solutions for Natural Hazards and Utility Resilience



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151	Key Problem Areas
152	Developing Socially Sustainable Solutions through Key Scientific Advances
163	Goals: Pathways Forward
164	Working Group Products
164	Hazard Mapping for Rural Utilities
165	Mutually Beneficial Collaborations with Utility Partners
169	Broadening the Infrastructure Conversation Beyond S3OK: Interdependencies, Emerging Technologies, and Transportation Resilience
169	Integrating Other Infrastructure and Considering Cascading Impacts
171	Strengthening Transportation–Grid Interdependencies
172	Adopting Novel Financial Tools for Utility Resilience
173	Navigating Compound Events: Addressing Emergent Risks in Utility Resilience
174	Insights for Future Collaborations
175	References

CHAPTER 9

Socially Sustainable Solutions for Natural Hazards and Utility Resilience

The Natural Hazards and Utility Resilience working group was established as a cornerstone of the S3OK initiative in response to the increasing complexity of extreme weather and climate-related challenges impacting Oklahoma's electrical grid. This group emerged from an iterative, three-year stakeholder engagement process (see chapter four), guided by feedback through OLAN and insights derived from EPSAN. Additionally, insights from targeted deep-dive conversations into critical issues such as [Extreme Weather and Oklahoma Infrastructure Interactions with a Wildfire Focus](#) and [Implementing Land Management Strategies for Water Use Efficiency in Agricultural Systems](#) provided initial inspiration for early discussions before specific goals were solidified. This working group was designed to bridge the gap between S3OK researchers and utility stakeholders, fostering collaborations to

enhance the physical resilience of the electrical grid and the broader infrastructure systems it supports.

The impetus for this collaboration is clear: Oklahoma's power grid resilience faces risks posed by extreme weather and climate conditions, including, but not limited to, drought, cold air outbreaks, and wildfire. These challenges underscore the need to develop solutions that integrate scientific research, advanced modeling, and stakeholder expertise. Simultaneously, S3OK researchers were developing novel datasets, predictive techniques, and key scientific innovations that showed promise for utility stakeholders, but needed real-world data to provide best results. Through collaborative efforts and a trusted partnership, S3OK researchers and utility partners joined together to share data,

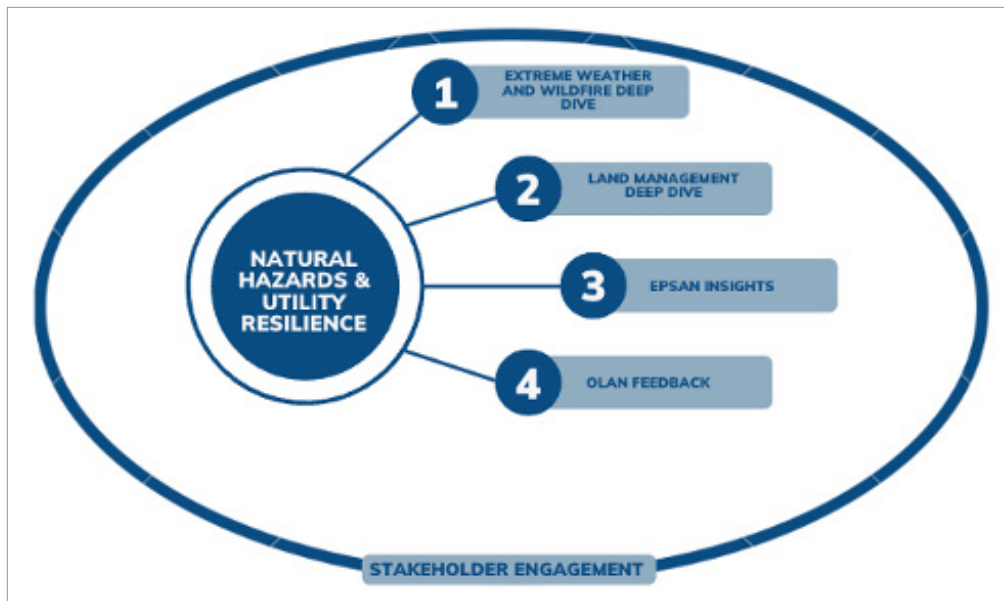


Figure 9.1: Natural Hazards and Utility Resilience Working Group Topic Identification Process Map

improve models, providing utility stakeholders with essential tools to mitigate risks to power grid resilience posed by extreme weather. Building on the significant progress made during the first four years of the S3OK project, the working group defined four primary goals for its fifth year:

1. **Foster Wider Collaboration and Opportunities to Share Tools and Knowledge between Research and Practice.**
2. **Seek Avenues to Better Incorporate Forecasting at a Specified Timescale as a Planning and Resilience Input/Tool.**
3. **Consider Impacts of Emerging Technologies and Renewable Energy Sources for Resilience Practices.**
4. **Increase the Availability and Awareness of Hazard Maps.**

This chapter outlines the collaborative research efforts undertaken by the Natural Hazards and Utility Resilience working group in pursuit of these goals and details the culmination of past achievements while charting a pathway for future efforts. Specifically, this chapter will address:

- The nature of the problems at the intersection of natural hazards and utility resilience in Oklahoma and the working group's response to these problems.
- How collaborative proposed solutions were developed through partnerships between electric utility stakeholders and S3OK researchers.
- Key scientific advances in relevant emerging technologies form the basis of proposed solutions
- How the working group's goals provide pathways forward to address these problems.
- The significance of working group products resulting from working group collaborations.

By synthesizing these elements, this chapter provides a comprehensive account of the progress made, highlights the utility of interdisciplinary collaboration, and offers actionable insights for future research and resilience-building initiatives.

Nature of the Problems: How Subseasonal to Seasonal Weather Drives Wicked Problems for Natural Hazards and Utility Resilience

The Natural Hazards and Utility Resilience working group focused on addressing the increasing vulnerabilities of Oklahoma's utility infrastructure in the face of new and intensifying natural hazards. The state's electrical grid and associated infrastructure are crucial to ensuring the security and well-being of its communities, both socially, economically, and environmentally. However, these infrastructures are deeply embedded within complex social and organizational systems. Moreover, they are under significant pressure from an evolving risk landscape characterized by quickly changing weather dynamics, increasing consumer demand, and aging infrastructure.

Events predicted at the subseasonal to seasonal (S2S) scale such as ice storms, wildfires, and extreme temperatures, challenge resilience by combining rapid onset, probabilistic forecasting uncertainties, and the compounding impacts of disrupted infrastructure. These events not only damage critical systems but also force difficult trade-offs between competing priorities for governments, utilities, and the public. Additionally, the compounding effects of climate change intensify these hazards, further complicating urban planning, disaster resilience, and environmental sustainability.

In response, the Natural Hazards and Utility Resilience working group leveraged S3OK's scientific, solutions-oriented approach to identify vulnerabilities and enhance resilience. By examining the interdependencies of infrastructure systems and addressing the societal challenges posed by extreme weather, the group worked collaboratively to develop innovative strategies that strengthen infrastructure resilience and reliability in the face of rapidly changing hazards around key problem areas.

What Is S2S Forecasting and Why Does It Matter for Infrastructure Planning?

Subseasonal to Seasonal (S2S) forecasting refers to predicting weather patterns 10 to 19 days in advance—longer than standard weather forecasts, but shorter than seasonal climate outlooks.

- **Why It Matters:** Critical hazards like ice storms, cold air outbreaks, and wildfires often develop in the S2S range and lie in a “predictability desert” where forecasting is especially difficult.
- **For Oklahoma Utilities:** Better S2S forecasts mean more lead time to prepare for peak energy loads, vegetation management, and infrastructure protection.
- **In Practice:** S3OK researchers have shown that certain critical hazards—such as cold air outbreaks—can be predicted 14–21 days in advance using jet stream and stratospheric data¹.

Investing in S2S forecasting capabilities can dramatically improve operational planning and emergency readiness.

Key Problem Areas

Throughout the S3OK project, the Natural Hazards and Utility Resilience working group identified four sets of interconnected, wicked problem areas. This section details the nature of the key problem areas identified by the working group and how the working group collaboratively responded to these problems with a scientific, solutions-oriented focus.

1) Infrastructure systems are deeply embedded within social and organizational systems.

Reliable infrastructure systems are essential for national security and the social, economic, and environmental well-being of communities. However, these infrastructure systems do not operate in isolation. Instead, they are deeply intertwined with social systems, including cultural values and organizational structures, which shape their functionality and resilience. Increasing hazards threaten physical infrastructure and expose vulnerabilities in the social and organizational systems that manage and rely on them. This presents a unique set of interconnected challenges to fostering infrastructure system resilience.

2) Ice storms pose a significant threat, but provide an opportunity to identify vulnerabilities in the utility grid.

Ice storms present a significant threat to the resilience of Oklahoma’s utility grid, as evidenced by the October 2020 ice storm. Occurring from October 26th to October 28th, this unprecedented event was the earliest Oklahoma ice storm recorded in meteorological history. The combination of early-season foliage and wintry precipitation resulted in numerous ice-laden tree limbs falling onto power lines across the region. The fallen tree limbs led to traffic interruptions and delays in repairing the damage to the electric power infrastructure, further complicating the challenges faced throughout the event. Additionally, power lines and power poles were damaged by ice and accompanying wind. This event highlighted vulnerabilities in the utility grid—the storm damaged over 4,200 power poles, along with hundreds of thousands of power lines, transformers, and other specialized equipment. At its peak, over 76,300 outages were recorded, affecting more than 350,000 customers. Ice storms, particularly those occurring early in the season, highlight the compounded risks of vegetation damage and infrastructure fragility, emphasizing the need to leverage innovative resilience strategies developed through collaboration between research and practice. By integrating these approaches, Oklahoma’s utility grid can become better equipped to withstand future ice storms, ensuring a more reliable utility system for Oklahomans^{2,3}.

3) **Extreme temperatures tax utility systems.**

Extreme temperatures pose significant challenges to utility systems by disrupting production capacity, straining delivery infrastructure, and altering demand patterns in unpredictable ways. In Oklahoma, multiple extreme temperature events throughout the S3OK project highlighted these vulnerabilities. Among the numerous extreme temperature events that occurred during the project, the February 2021 North American cold air outbreak stands out for its wide-ranging impacts. This event severely disrupted the natural gas network, power grid, transit networks, and water systems, exposing critical interdependencies and cascading failures^{4,5,6,7}.

4) **Wildfires pose an increasing threat in Oklahoma, necessitating enhanced predictive modeling and a better understanding of public risk perception.**

Wildfires are an escalating threat in Oklahoma, driven by the region's vulnerability to precipitation extremes and rapid transitions between wet and dry conditions. These fluctuations, characteristic of the Southern Great Plains, significantly impact critical infrastructure systems such as electric power and potable water while straining agricultural communities and urban areas alike⁸⁻¹⁵. Periods of heavy rainfall foster abundant vegetation growth, which, when followed by drought, dry into highly flammable fuel for wildfires. This dynamic is further intensified by the rapid expansion of Eastern Red Cedar, a highly flammable invasive species that thrives in wet conditions and greatly increases wildfire risk when dried. Moreover, when wildfires do occur, they can dramatically alter landscape carbon balances, water quality, and infrastructure resilience.

Developing Socially Sustainable Solutions through Key Scientific Advances

Addressing the complex challenges at the intersection of natural hazards and utility resilience requires both scientific innovation

and sustained collaboration. In response to key problem areas identified throughout the project, the Natural Hazards and Utility Resilience working group advanced a suite of science-informed solutions designed to address the resilience of interdependent infrastructure systems. These efforts acknowledged critical trade-offs while advancing knowledge in areas identified above. This section highlights the scientific advances that are helping to shape a more adaptive and resilient future for the utility industry within key problem areas.

Solution to Key Problem Area: Infrastructure systems are deeply embedded within social and organizational systems.

To effectively address challenges regarding the embedded nature of infrastructure and social systems, S3OK researchers adopted **An Analytic Approach to Manage Evolving Environmental Risk** to understand evolving environmental threats and made strides in **Addressing Public Concern and Willingness to Pay for Grid Resilience in Oklahoma**.

An Analytic Approach to Managing Evolving Environmental Risk

As the risk of wildfires associated with electricity transmission and distribution infrastructure increases, utilities face increasingly complex decisions about where and when to invest in measures to prevent fire ignitions. These decisions have significant economic consequences, as utility-operated equipment, while responsible for only 1–5% of fire ignitions in regions like Southern California, is responsible for a much higher proportion of the total area burned—up to 30%—and over 80% of the damages caused by wildfires¹⁵. These stakes are high because wildfires can damage not only the infrastructure but also the communities and ecosystems that depend on it. To manage this risk, many states have implemented regulations that hold utilities financially accountable for the damage caused by fires ignited by power lines. These regulations vary across jurisdictions, with some states requiring utilities to be fully liable for fire damages

regardless of their efforts to prevent ignitions. In contrast, others offer liability limits for utilities that take specific preventative actions.

Malloy (2024)¹⁷ investigated how utilities' strategies to prevent fire ignitions change under different regulatory environments, using data from 2018 to 2020 in California, to provide insights for parallel contexts in Oklahoma. He found that utilities are more likely to invest in fire prevention measures when they face higher financial liability, but this effort peaks when the potential cost of a fire ignition threatens the utility's overall asset value. This pattern suggests that regulations that set clear standards for fire prevention and limit utilities' financial responsibility for damages, if those standards are met, effectively incentivize action. By focusing on the economic incentives and regulatory frameworks that shape utility behavior, S3OK researchers highlight how infrastructure decisions are embedded in complex social and organizational systems. These decisions are not just driven by technological or financial factors but also by regulatory policies, organizational structures, and societal expectations. This perspective is critical for understanding how utilities make risk management decisions and how those decisions can be influenced to enhance infrastructure resilience and wildfire prevention.

Addressing Public Concern and Willingness to Pay for Grid Resilience in Oklahoma

Public concern about the reliability of Oklahoma's electrical grid and willingness-to-pay (WTP) for improvements are critical factors in shaping energy policy and investment in grid resilience. Using data from Wave 2 of the EPSCoR S3OK M-SISNet survey (n=2,108), S3OK researchers examined what factors were associated with concern for the current state of the electrical grid in Oklahoma and willingness-to-pay (WTP) for electrical grid improvements in the state using a conceptual model based on past research and theories of risk. Results from statistical modeling indicate that people who perceive higher weather-related and power outage risks hold greater

concern for the state of electricity infrastructure in Oklahoma. Additionally, those with lower trust in those responsible for maintaining the grid express heightened concerns about electricity infrastructure, indicating that confidence in grid operators plays a significant role in shaping public perception¹⁸.

Understanding what influences WTP for grid improvements is key to developing policies that garner public support. Findings suggest that people are more likely to support and pay for grid enhancements when program costs are kept low. Additionally, politically liberal and non-white residents, as well as those who demonstrated greater trust in grid maintenance efforts and who recognize the risks of outages, show a greater willingness to pay for grid improvements. These insights underscore the significance of public trust and transparent communication in energy policy decisions.

These findings highlight the need to address public concerns and build support for resilience investments effectively. Educational campaigns that emphasize the real-world benefits of grid improvements, such as reduced outage risks during severe weather events, long-term cost savings, and enhanced energy security, can help increase public buy-in. Furthermore, incorporating public input into infrastructure planning and ensuring reliable access to grid improvements can strengthen trust and encourage participation in resilience programs. **By aligning policy decisions with public concerns and financial considerations, Oklahoma can create a more secure, sustainable, and widely supported electrical grid for the future.**

Solution to Key Problem Area: Ice storms pose a significant threat, but provide an opportunity to identify vulnerabilities in the utility grid.

Recognizing that the October 2020 ice storm event provided an invaluable opportunity for S3OK stakeholders to collaborate, S3OK researchers worked with the Oklahoma Electric Cooperative (OEC) to develop a novel opportunity

to study the resilience of Oklahoma's electric distribution network.

Three research efforts stemming from this collaboration have deepened understanding of the grid's vulnerabilities and informed strategies for hardening and resilience. This includes S3OK researcher efforts to develop a **Probabilistic Framework for Assessing Ice Storm Resilience**, complete a **Resilience Analysis of Electric Distribution Networks**, and explore **Strategies for Photovoltaic Expansion in Oklahoma**.

Probabilistic Framework for Assessing Ice Storm Resilience

First, Hou et al. (2023)² and Hou and Muraleetharan (2023)¹⁹ developed a probabilistic framework to evaluate the resilience of power distribution systems during ice storms and to explore hardening strategies. Their work utilized detailed fragility models for power distribution systems that accounted for factors such as falling trees and limbs, ice accumulation, and wind effects, including speed and direction (Figure 9.2, 9.3). S3OK researchers used an empirical fragility function to model tree damage using satellite images from the October 2020 storm and applied it to a portion of the OEC network. By doing so, S3OK researchers were able to identify vegetation management as a cost-effective approach to improving system resilience. This finding underscores the importance of timing vegetation management practices, especially before early-season storms.

Resilience Analysis of Electric Distribution Networks

Further, Panchalogaranjan et al. (2023)³ examined the reliability and resilience of electric distribution networks during High Impact Low Probability (HILP) events, such as the October 2020 ice storm. They utilized OEC's network and outage data to evaluate traditional reliability indices such as the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) and demonstrated that these indices frequently fail to accurately capture the dynamic disruption and restoration behavior

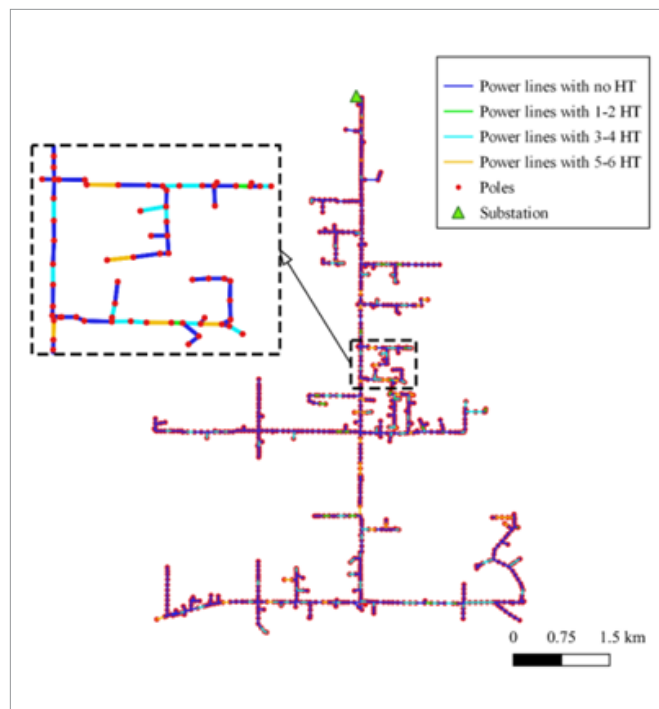


Figure 9.2. A power distribution network in Oklahoma (Note: HT refers to hazard trees) (Hou et al. 2023)²

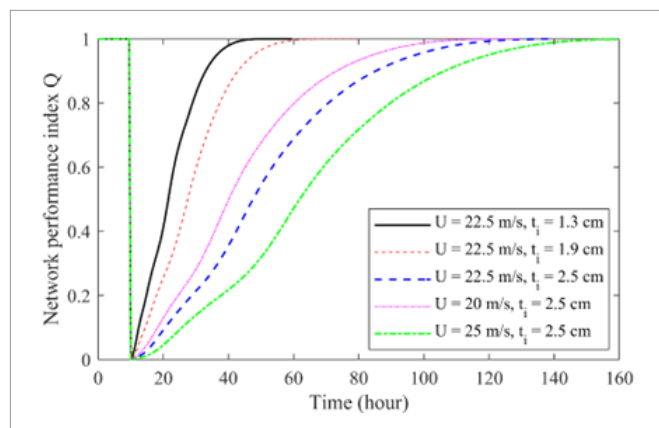


Figure 9.3. Network restoration curves for ice storms with different wind speeds (U) and ice thicknesses (t_i) (wind direction perpendicular to the power lines) (Hou et al. 2023)²

of networks during such events. Their research also showed that the traditional trapezoidal resilience curve does not fully characterize the resilience of a network undergoing dynamic restoration. Furthermore, they highlighted the potential of adaptive electrical infrastructure, such as automated switching systems, to significantly enhance network resilience by minimizing disruptions and accelerating recovery times.

Balancing Renewable Energy Integration and Grid Stability: Strategies for Photovoltaic Expansion in Oklahoma

Oklahoma's unique geography has immense potential to enhance grid resilience by leveraging its abundant solar resources, yet photovoltaic (PV) integration remains limited, with most renewable energy in the state sourced from wind power. Expanding PV generation, especially at the distribution level, offers a critical opportunity to expand energy sources, reduce dependency on centralized power, and strengthen the grid. Research has shown that PV systems, as distributed energy resources (DERs), improve grid resiliency by generating power closer to where it is consumed. However, integrating PV systems into the existing grid poses challenges, such as managing voltage stability, thermal capacity, and fault protection coordination²⁰.

To address these challenges, S3OK researchers conducted a locational-dependent PV hosting capacity (PVHC) analysis using a detailed test feeder provided by the OEC. This real-world 24.9 kV feeder, with 570 three-phase nodes and a peak load of 5.2 MW, served as a real-world model to evaluate how much PV generation a distribution feeder can accommodate without violating grid operational constraints. Using the Particle Swarm Optimization (PSO) method, this study efficiently identified the optimal PV sizes and locations for integration of PV systems into the Oklahoma distribution network without compromising grid reliability²⁰. This approach significantly reduced simulation times while maintaining accuracy, providing a systematic method for determining safe and efficient PV penetration levels across Oklahoma's feeders. Such insights are crucial for expanding PV adoption while ensuring the grid operates reliably.

In addition, a separate study examined how integrating centralized and residential PV systems, along with electric vehicle (EV) charging stations, impacts fault currents and protection coordination in Oklahoma's grid²¹, using steady-state fault analysis. In particular, this study examined symmetrical and unsymmetrical fault scenarios

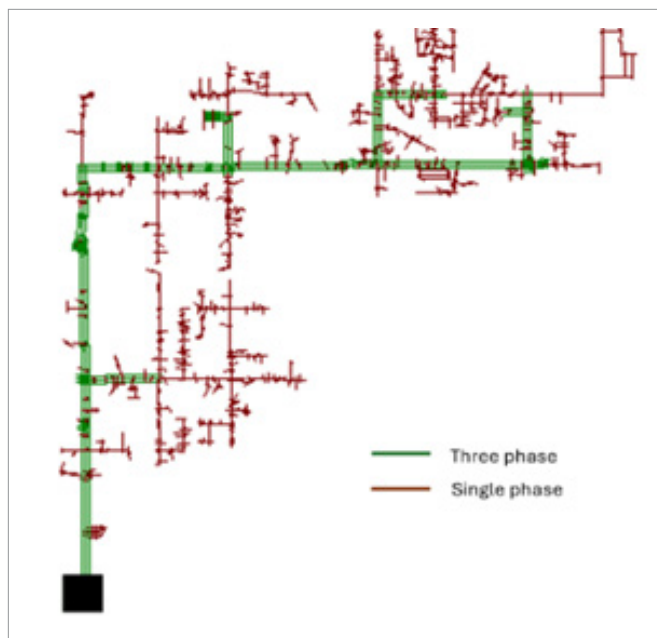


Figure 9.4: OEC distribution feeder used for PV integration studies

to explore their impact on protection device coordination. The results revealed that while residential PV systems and EV loads have minimal effects on fault levels, large-scale centralized PV systems can significantly alter fault dynamics, complicating fault clearance and protection reliability. This finding underscores the necessity for adaptive protection schemes to address these challenges and maintain grid stability as distributed energy resource (DER) penetration increases.

Together, these studies provide a clear roadmap and actionable insights for advancing Oklahoma's renewable energy integration while enhancing grid resilience. The PVHC analysis enables utilities to identify the optimal level of PV penetration for each feeder, avoiding risks such as voltage violations and thermal capacity overloads. Simultaneously, the fault analysis highlights the importance of updating protection systems to accommodate the operational complexities associated with high DER penetration. **By applying advanced modeling techniques and real-world data, these strategies offer a practical path forward for Oklahoma to capitalize on its solar potential, meet renewable energy goals, and build a more resilient and sustainable energy future.**

PV Hosting Capacity (PVHC): A Planning Tool for Distributed Solar Energy

PV Hosting Capacity is the maximum amount of solar energy (photovoltaic, or PV) a power distribution feeder can accept without causing reliability issues like voltage instability or thermal overload.

Why It's Important: As Oklahoma expands its solar footprint, utilities need to know where and how much PV can be safely integrated.

How It Works: PVHC studies use optimization algorithms and system simulations to test different scenarios for solar placement and load conditions.

In Action: S3OK researchers partnered with OEC to test PVHC using real Oklahoma feeder data and optimization tools like Particle Swarm Optimization.

Practitioners can use PVHC analysis to guide solar deployment and grid upgrades in ways that reduce risk and improve resilience.

Key Problem Area: Extreme Temperatures Tax Utility Systems

In response to challenges surrounding the impact extreme temperatures have on Oklahoma's utility systems, the Natural Hazards and Utility Resilience working group researchers dynamically adapted their research scope to address these emergent and ongoing hazards. In particular, they aimed to identify **Strategies for Enhancing Resilience Across Utility Systems** in the face of climate-exacerbated risks by focusing on the 2021 North American cold air outbreak's impact on Oklahoma and neighboring Texas. S3OK researchers also made efforts toward **Improving Prediction Skill for Cold Air Outbreaks Across the Central US** and used **Subseasonal Circulation Patterns to Predict Peak Power Demand**.

Strategies for Enhancing Resilience Across Utility Systems: Insights from the Texas Power Grid

The February 2021 North American cold air outbreak, which most notably devastated the Texas power grid, provided a critical opportunity to analyze and compare the performance

of neighboring power systems, including the Southwest Power Pool (SPP) that monitors and directs the electric utility grid Oklahoma. Unlike the 2020 winter ice-storm just 4 months prior, the extreme weather in February 2021 did not cause any significant infrastructure damage in Oklahoma. Rather, because of freezing temperatures, a lack of available supply combined with surging electricity demand led to excessive forced outages that narrowly avoided a complete grid collapse. By examining publicly available historical system performance data, including load loss, generation mix, and resource adequacy, the research team identified key factors contributing to system failures²². This study highlighted often-overlooked dynamics that were critical to power network performance in Oklahoma, including SPP's foresight in coordinating generation dispatch across member states, which mostly mitigated impacts in Oklahoma. In contrast, the Texas grid's isolated architecture, with minimal capacity for power imports, exacerbated its crisis. Furthermore, the analysis revealed that interdependencies between electricity and natural gas infrastructure were the primary drivers of outages, stemming from a 15-year-long evolution in increased reliance on natural

gas. This study also revealed that, contrary to widespread narratives, renewable energy played a minimal role in the outage. Electric Reliability Council of Texas' (ERCOT's) resource adequacy planning did not rely on wind or solar energy during winter peaks. While some 50% of wind turbines experienced icing-related failures, their actual output exceeded forecasted levels. These findings emphasize the importance of grid interconnectivity, maintaining a heterogeneous energy mix, and proactive contingency planning to enhance resilience against climate-driven hazards.

Improving Prediction Skill for Cold Air Outbreaks Across the Central US

Cold air outbreaks (CAOs) are episodes of extremely low temperatures that affect relatively large regions and are associated with the invasion of cold air out of the high latitudes from southward dips in the jet stream^{23,24}. These events have substantial socioeconomic impacts; in the United States alone, cold air intrusions and associated wintry stormy weather cost an average of \$4.2 billion per event between 1980 and 2024²⁵. The February 2021 North American CAO, which hit Oklahoma and the Southern Plains especially hard, was particularly costly^{4,6}.

Prompted by these events, members of the working group focused on making key scientific advances that could be used to improve long-lead predictions of extreme climate anomalies (CAOs) in the Central United States. Millin et al. (2022)⁶ developed the first-of-its-kind CAO database for the Central US, dating back to 1950. They found that despite winters rapidly warming over time, the February 2021 CAO was the second-most severe to affect the region; the most severe CAO in the Central United States occurred on December 16th, 1983. Millin et al. (2022)⁶ also found that CAOs in the region occur under two specific weather regimes: (1) the Arctic High regime, featuring higher-than-normal pressure across the Arctic regions, displacing frigid air masses southward; and (2) the Alaskan Ridge Regime, featuring a blocking high pressure system over the Gulf of Alaska that forces air masses from Siberia to cross the Arctic Ocean and invade central and eastern North America. Recognizing

these regimes, the team also tied their formation to subseasonal (up to 14 days ahead of the start of the CAO) predictors including overall weakness in the stratospheric polar vortex (Arctic High CAO events) and a combination of changes in tropical convection and a phenomenon known as stratospheric wave reflection (Alaskan Ridge CAO events).

Other studies quantified how well these predictors performed in forecasts. For the February 2021 CAO event, Millin and Furtado (2022)⁶ demonstrated that several runs of operational subseasonal forecast models successfully captured the threat of the CAO up to 3 weeks in advance. The key difference between the best-performing and worst-performing models lay in how they handled two specific jet stream configurations, two days ahead of the event's onset: one in the East Siberian Sea and the other in the Northwest Atlantic. This result highlights a key benchmarking tool for other forecasters of extreme CAOs and a process-oriented diagnostic that modelers can use for future model enhancements. **Combined, these advances provide a scientific foundation for more reliable, longer-range forecasts, and equip utility planners and forecasters with powerful tools to better anticipate and prepare for extreme winter weather.**

Using subseasonal circulation patterns to predict peak power demand

Subseasonal large-scale circulation patterns provide a powerful and innovative tool for predicting peak power demand in the Southwest Power Pool (SPP) region. S3OK researchers²⁶ demonstrated that recurring large-scale weather patterns, such as the large-scale recurrent circulation patterns mentioned above, have a significant influence on temperature variations. These temperature variations, in turn, influence subseasonal temperature forecasts and peak power demand in the cold season months in the region. For example, when patterns during the fall or winter resemble the Alaskan or West Coast Ridge, the SPP is 50% to 100% more likely to exceed peak power demand. On the other hand,

milder weather regimes, such as the Pacific Trough and Arctic Low, reduce the chances of peak demand spikes²⁶.

These findings are crucial because they provide potential for utility planners to directly connect weather patterns to the conditions that drive heating needs and energy use. Furthermore, such weather regimes are predictable with reasonable accuracy up to 14 to 20 days in advance²⁷. This means energy providers could look ahead nearly three weeks to identify periods of potential stress on the power grid. By integrating these forecasts into their planning processes, utility operators can proactively manage resources, ensure grid stability, and reduce the risk of outages during high-demand periods. **Such forward-looking strategies can also lead to cost savings and more efficient energy distribution, benefiting both providers and consumers.**

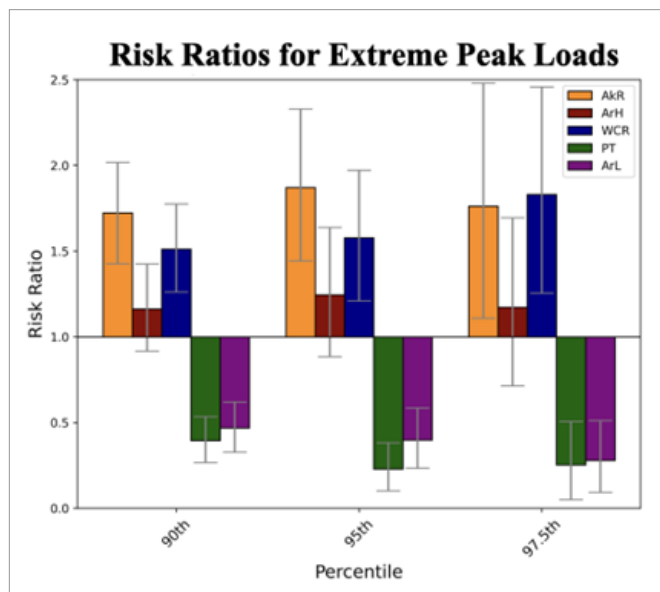


Figure 9.5 The risk of exceeding extreme peak loads in the Southwest Power Pool nearly doubles during the Alaskan Ridge and West Coast Ridge regimes. The relative risk of extreme peak load as a function of North American winter weather regimes (bars) for the 90th, 95th, and 97.5th percentile extreme thresholds as compared to all winter days. Whiskers represent the 95th percentile confidence interval for each risk ratio. Adapted from Millin et al. (2024)²⁶.

Key Problem Area: Wildfires pose an increasing threat in Oklahoma, necessitating enhanced predictive modeling and a better understanding of public risk perception.

In response to emergent hazards related to wildfires in Oklahoma, working group members collaborated to **Enhance Wildfire Forecasting and Better Understand Shifts in Public Risk Perception Following Wildfire Events**, as both are central to ensuring practitioners and the public are informed and better able to perceive and respond to wildfire threats. Recognizing these challenges, the Natural Hazards and Utility Resilience working group developed science-driven strategies to mitigate wildfire risks and their impacts on critical systems. The group leveraged insights from studies on precipitation anomalies and vegetation patterns that identify increased chances for wildfire months in advance. This predictive capability enables utility managers to optimize maintenance schedules, such as strategic vegetation management near power lines, and implement grid-hardening measures to reduce vulnerability during high-risk seasons. By integrating cutting-edge research with practical solutions, the working group has produced scientific products that have the potential to advance Oklahoma's ability to prepare for and respond to wildfire threats, protecting both community well-being and infrastructure resilience.

Enhance Wildfire Forecasting

S3OK researchers made significant strides in predicting wildfire risk in Oklahoma through advances in predictive modeling. Puxley et al. (2024)¹⁵ have shown that "precipitation whiplash" events—sudden shifts from wet to dry conditions—play a pivotal role in driving wildfire activity in the Oklahoma and Texas Panhandles. By examining the 2017–2018 wildfire season, the researchers found that above-average spring vegetation growth, followed by a wet summer and a dry winter and spring, left vegetation dry and highly flammable. Hence, precipitation whiplash events such as wet summers followed rapidly by dry falls and winters had a strong correlation with

increased wildfires and acres burned the following spring (Figure 9.6).

The 2017 season presents a striking example, where precipitation reached 137% of normal during the growing season. This increased precipitation fostered dense vegetation growth. However, this was followed by an abrupt transition to drought, with winter rainfall dropping to just 21% of normal and drought conditions intensifying to the highest severity level (D4—exceptional drought). This sequence of events culminated in an above-average wildfire season in spring 2018, underscoring the impact of rapid wet-to-dry transitions on wildfire proliferation. This research highlights how enhanced modeling and monitoring of seasonal precipitation patterns and rapid transitions can inform wildfire forecasts

months in advance. By integrating these insights into predictive models, decision-makers can take proactive steps, such as improving vegetation management and fortifying infrastructure in high-risk areas. These advancements offer practical tools to strengthen resilience against wildfires, protecting Oklahoma's landscapes, communities, and critical systems.

Understanding Shifts in Public Risk Perception Following Wildfire Events

Using the March 2023 wildfire outbreak in Oklahoma as a case study, S3OK researchers led by Campos et al. (2024)²⁸ advanced understanding of public risk perception and awareness of wildfires. The March 31, 2023, wildfire outbreak in Oklahoma (see Figure 9.8) exposed

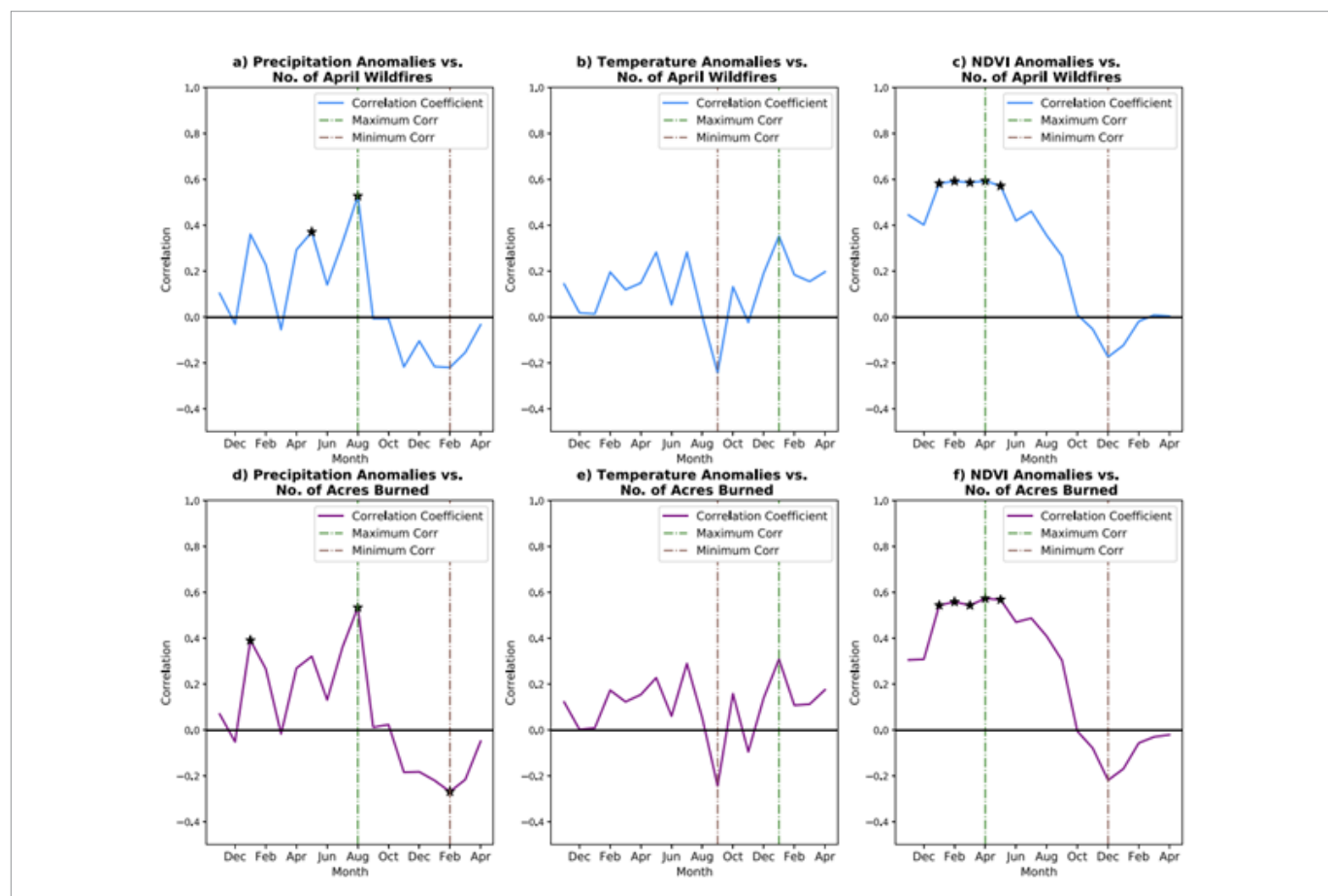


Figure 9.6: The lag correlation coefficient between the number of April wildfires and (a) precipitation anomalies, (b) temperature anomalies, (c) NDVI anomalies, and the number of acres burned by April wildfires and (d) precipitation anomalies, (e) temperature anomalies, (f) NDVI anomalies. All values are domain-averaged across the study domain (see Puxley et al. 2024 for more details). The green and brown dashed lines show the maximum and minimum correlation coefficients, respectively, and the black stars show correlations that are significant at the 95% level, calculated using Monte Carlo.

the devastating impact of extreme weather and underscored the importance of proactive wildfire risk management. The outbreak was driven by extreme meteorological conditions, including unusually high temperatures, strong winds, and a sharp drop in humidity. For example, at the Guthrie Mesonet station (see Figure 9.9), pre-wildfire temperatures soared to an average of 70.4°F—far above the typical March average of 56.5°F—while humidity levels plummeted from 80% to just 9% in a matter of hours. Winds reached speeds of 39 m/s, with gusts up to 56 m/s, accelerating the spread of the fires. Compounding these conditions, prolonged drought left soil moisture critically low, with the fractional water index at only 0.50 cm at a 5 cm depth. These factors combined to fuel wildfires that spread rapidly, impacting both urban and rural communities and exposing vulnerabilities in Oklahoma's changing biomes, particularly in areas near urban developments.

In the aftermath of the March 2023 wildfire outbreak, public awareness of wildfire risk surged.

Responses to the M-SISNet survey collected before and after the fires revealed significant increases in perceived current and future wildfire risk perception, showing the psychological impact of experiencing this natural hazard. Relatedly, trust in the private sector and in policymakers before and after the firestorm eroded (see Figure 9.7).

Meanwhile, older individuals, women, and those with lower trust in policymakers and private companies or with less conservative political views reported the highest levels of concern²⁹. These insights highlight how direct experiences with wildfires, individual demographic differences, and trust can shape risk perceptions. This understanding offers a valuable opportunity to improve community preparedness and resilience by offering the insight that can shape the development of tailored education and outreach efforts. By leveraging increased awareness and addressing community-specific needs, Oklahoma can better prepare for and mitigate the impact of future wildfire events.

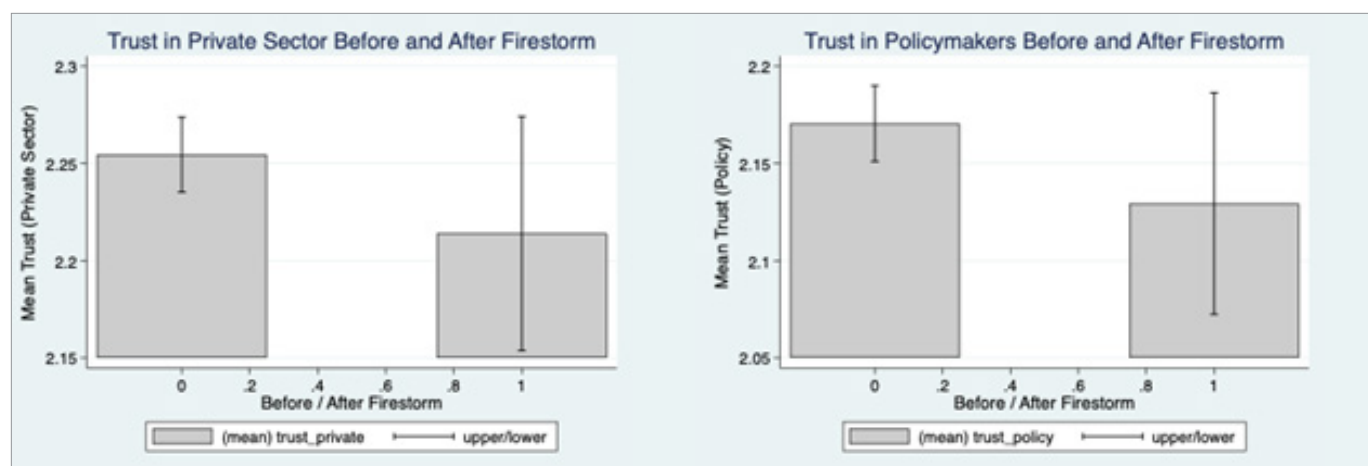


Figure 9.7 Mean trust in Private Sector and Policymakers before and after Firestorm

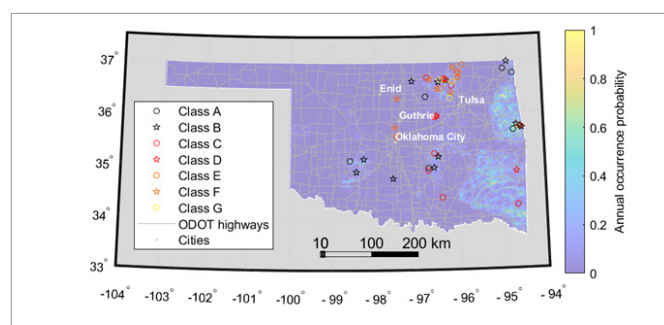


Figure 9.8. Locations of the wildfires during the outbreak (from Campos et al. 2024).

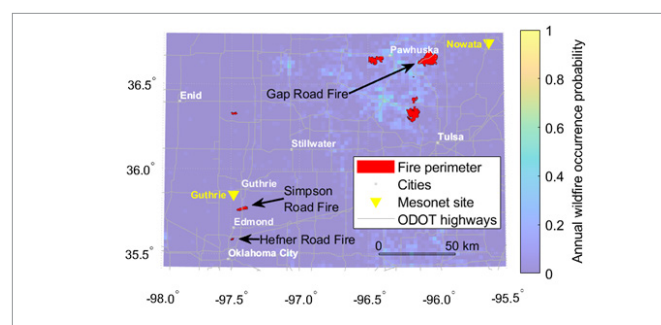


Figure 9.9. Locations of the wildfires during the outbreak (from Campos et al. 2024).

Rural Utility Cooperative Perspective on Wildfire Risk

Wildfire risk is an increasingly pressing issue for rural electric cooperatives, particularly as extreme fire events in states like California and Colorado highlight vulnerabilities in electric utility infrastructure. Though destruction at the scale seen in recent years in other regions has not been observed in Oklahoma, wildfire threats have long been a concern for rural utility cooperatives. Damage to utility infrastructure, such as burned power poles and downed lines, results in costly repairs, service disruptions, and potential liability challenges.

Challenges of Wildfire Risk for Rural Utilities

One of the biggest concerns for rural utilities is the rising cost and availability of insurance. Due to past wildfire incidents where utilities were deemed responsible for fire ignition, securing wildfire coverage has become increasingly difficult. Insurers are either excluding wildfire coverage from general liability policies or significantly raising rates due to the potential for large damage settlements. In cases where utilities are found liable, they can face lawsuits amounting to millions of dollars, costs that ultimately get passed down to consumers. Rural electric cooperatives, which aim to keep rates affordable for their members, struggle to balance financial risk mitigation with the rising cost of insurance. Additionally, legal disputes often arise over whether wildfire damage should be classified as an “act of God” or attributed to utility negligence. The burden of proof often falls on the utility, requiring them to demonstrate extensive mitigation efforts to maintain eligibility for insurance policies. This makes proactive fire prevention strategies critical not only for infrastructure protection but also for financial sustainability.

Wildfire Mitigation and Preparedness Strategies

To reduce liability exposure and improve overall grid resilience, rural cooperatives are investing in mitigation strategies, including:

Vegetation Management & Fuel Load Monitoring: Regular inspections of power line corridors and vegetation clearance efforts help reduce fire ignition risks. Advanced mapping of fuel loads and strategic maintenance of high-risk areas could enhance these efforts.

Prescribed Burns as a Risk Reduction Tool: When weather conditions permit, controlled burns can help manage excessive fuel loads, though high winds present a challenge.

Infrastructure Hardening: Metal poles offer greater fire resistance than traditional wooden poles, though they come at a higher cost, necessitating careful cost-benefit considerations.

Weather Forecasting & Fire Risk Alerts: Existing fire weather alert systems, such as the SPIA fire-spread index, help utilities monitor fire-conductive conditions (e.g., low humidity and high winds) and adjust operations accordingly. More sophisticated predictive tools, like those developed in S3OK collaborations outlined here, could further enhance preparedness.

Strategic Investment in Targeted Inspections: If utilities have access to real-time data on fuel loads and high-risk zones, they can prioritize inspections and allocate resources more efficiently. Recently, this has resulted in new grid monitoring devices for wildfires including installing artificial intelligence based cameras, additional circuit fault current indicators (CFCIs) and adaptively readjusting fault protection relay settings for wildfire prone areas.

The Role of Insurance and Risk Management

Insurance carriers are more likely to provide coverage to utilities that demonstrate strong mitigation plans, proactive vegetation management, and the use of advanced forecasting tools. Having access to better risk assessment tools, such as predictive mapping of fire-prone areas, could strengthen utilities' ability to secure coverage at reasonable rates. This, in turn, would benefit consumers by limiting cost increases while ensuring greater grid stability.

Additionally, financing mechanisms such as catastrophe bonds (CAT bonds) can help rural utilities transfer catastrophe risk to capital market investors, providing an alternative to traditional reinsurance. Such mechanisms could enhance financial resilience by providing robust risk management options and offer a competitive alternative to catastrophe insurance, depending on market conditions. Given the limited research and development budgets of many electric cooperatives, partnering with academia could help these businesses explore such solutions for resilience enhancement. As part of this working group, the S3OK team is working to advance scientific literature on CAT bonds.

While wildfires in Oklahoma may not reach the scale of those in the western U.S., their impact on rural communities, including damage to fences, homes, and livestock, remains significant. Ensuring that rural electric cooperatives have access to the necessary resources, data, and support to mitigate wildfire risks will be essential in maintaining reliable and affordable power for rural communities.

Ultimately, as one cooperative representative put it, **"This country runs on infrastructure—these lights aren't on without the grid. It's a challenge to keep it up, but whatever we can do, even if it's incremental, is worth it."**

Goals: Pathways Forward

Recognizing the evolving challenges posed by extreme weather and climate variability, including those detailed above, the working group outlined a series of goals that build upon the foundational scientific advances completed in the initial four years of the S3OK initiative. These goals, introduced at the start of this chapter, served as a roadmap for targeted action, ensuring that research-driven insights translate into practical, scalable solutions for utility stakeholders. Below, we expand upon these goals and highlight how these goals provide pathways forward and inspire the development of select working group products described in the next section.

Recognizing the gap between researchers and industry practitioners, the working group sought to **foster wider collaboration and opportunities to share tools and knowledge between research and practice**. Throughout S3OK, this included initiatives that:

- Expanded partnerships with electric utility cooperatives, regulatory agencies, and emergency management professionals and are evident in collaborations discussed throughout this section.
- Established recurring knowledge-sharing forums through deep dive conversations and working group meetings that ensured cutting-edge research on extreme weather impacts and grid resilience reached decision-makers.
- Developed a digital repository for tools, case studies, and best practices to enhance accessibility and implementation of resilience strategies accessible to all working group members.

Given the increasing precision of climate and weather forecasting, the working group's second goal was to **seek avenues to better incorporate forecasting at a specified timescale as a planning and resilience input/tool**. In alignment with this goal, the working group:

- Strengthened collaborations across the range of scientific (e.g., social scientists, meteorologists, and engineers) and practitioner expertise to develop and refine forecast tools relevant to infrastructure planning horizons (e.g., short-term operational forecasts and long-term resilience planning).
- Piloted test predictive models with utility stakeholders to assess usability and integration into decision-making frameworks.

In line with the third goal, **members of the working group advanced analysis that considered the expansion of renewable energy and grid modernization**. In particular, this included key works described above that:

- Assessed how increased deployment of distributed energy resources (DERs), battery storage, and microgrids can enhance grid stability and reduce vulnerabilities to extreme weather events.
- Evaluated the implications of renewable energy siting and transmission and distribution network expansion on wildfire risk and grid reliability.
- Considered public concern and willingness-to-pay to gauge public support for developing resilient energy utility systems.

The fourth and final goal the working group established was to **increase the availability and awareness of hazard maps to relevant stakeholders in Oklahoma**. To advance these efforts, members of the working group collaborated across the S3OK network to:

- Expand and refine hazard mapping efforts, incorporating new data on wildfire risk, flood exposure, and extreme temperature vulnerabilities.
- Discuss the development of interactive hazard maps tailored for utility planners, emergency managers, and policymakers.
- Conduct targeted outreach and training to increase awareness of existing hazard mapping tools and ensure their integration into resilience and emergency response planning.

Working Group Products

The aforementioned goals guided the development of concrete working group products that strengthen resilience planning and facilitate long-term collaboration. The following key deliverables serve as tangible outcomes of the working group's efforts and serve as a springboard for collaborations beyond S3OK:

Hazard Mapping Resources – Expansion of hazard maps that integrate climate projections, wildfire risks, and utility infrastructure vulnerabilities.

Mutually Beneficial Collaborations – Establishment of research-practice networks that align academic expertise with real-world utility resilience challenges and meet specific needs.

By advancing these pathways, the working group will continue to serve as a vital bridge between scientific research and infrastructure resilience planning, ensuring that Oklahoma's utility stakeholders have the knowledge and tools necessary to navigate an increasingly complex risk landscape.

Hazard Mapping for Rural Utilities

In response to the need to augment rural utility capacity to identify and respond to emergent hazards, the working group conducted an evaluation of outage reliability and resiliency to **enhance power distribution system resilience and address the critical intersection of wildfires and electrical infrastructure**. In these instances, open collaboration and, when necessary, data sharing made the development of usable products possible.

Enhancing Power Distribution System Resilience through Data Sharing and Hazard Mapping

The collaboration between S3OK researchers and Oklahoma Electric Cooperative (OEC) described in [“Solutions to Key Problem Area: Infrastructures are deeply embedded within social](#)

[and organizational systems”](#) exemplifies how data sharing can significantly enhance hazard mapping and resilience planning for rural utilities. The ability to evaluate and implement strategies to mitigate the impact of extreme weather events, such as the October 2020 ice storm, relied on access to detailed electrical infrastructure datasets provided by OEC. These datasets enabled researchers to assess system vulnerabilities, optimize restoration processes, and develop hazard maps that integrate real-world utility data to improve preparedness and response capabilities.

Leveraging Data for Resilience Analysis and Power Restoration

OEC's provision of electrical network data and storm outage records was instrumental in evaluating power system resilience. The data included detailed electrical power line configurations, customer loads, equipment specifications for transformers, fuses, switchgear, protection relays and reclosers, and outage reports, which allowed researchers to analyze the storm's impact at a granular level. Using this information, S3OK researchers:

Computed outage reliability and resiliency indices to measure system performance before, during, and after the storm.

Analyzed outage duration trends to assess vulnerabilities in power distribution.

Simulated service restoration scenarios to compare the effectiveness of different grid management strategies, including automated restoration techniques and power flow redirection.

Findings from these analyses³ highlighted the potential of advanced restoration strategies, such as automated reconfiguration and fault isolation, to minimize service disruptions and enhance the resilience of the distribution system against future extreme weather events. The work is currently being extended to investigate on-the-horizon technologies such as wireless roadway charging

of electric vehicles and how that impacts grid operations.

Data-Driven Strategies for Grid Hardening and Hazard Mitigation

Beyond outage analysis, OEC's network data provided critical insights into proactive resilience strategies. Researchers used the data to:

- Assess the effectiveness of pole upgrades and vegetation management in mitigating ice storm damage.
- Identify infrastructure vulnerabilities to prioritize investments in structural reinforcement and adaptive maintenance.
- Develop hazard maps integrating electrical infrastructure with known environmental risk factors, such as tree encroachment, icing risks, and substation exposure, to improve predictive risk modeling and preemptive response planning.

This data-driven approach demonstrated how electrical network mapping and hazard assessment can enhance rural utilities' ability to prepare for and respond to severe weather threats².

Advancing Renewable Energy and Grid Modernization with Feeder Data

OEC's feeder-specific data played a crucial role in evaluating the resilience of the grid under changing energy demands and evolving technology landscapes. By sharing hourly feeder load profiles, the cooperative facilitated research into:

- The integration of renewable energy sources such as photovoltaic (PV) generation, simulating how solar energy interacts with feeder demand²⁰.
- The impact of electric vehicle (EV) adoption on fault levels, assessing potential grid vulnerabilities under different PV-EV scenarios²¹.
- The increasing electrification of transportation and resulting effects on voltage stability,

consumer demand patterns correlated with driving habits and charging-station loads combined with roadway wireless charging scenarios.

This research underscores the importance of utility-academic partnerships in designing future-ready electrical systems, where real-world data enhances modeling efforts to improve renewable energy adoption, strengthen grid stability, and optimize hazard response strategies.

Building Resilience through Collaborative Hazard Mapping

By fostering a robust exchange of utility infrastructure data, S3OK researchers and OEC have laid the groundwork for usable, high-resolution hazard maps tailored to rural electric cooperatives. These hazard maps:

- Integrate real-world outage, weather, and grid vulnerability data, providing actionable insights for risk assessment.
- Enhance operational decision-making, guiding preemptive power system reinforcements.
- Support resilience planning efforts, ensuring that rural utilities can anticipate and mitigate extreme weather impacts.

This partnership demonstrates how data-driven collaborations can bridge the gap between research and practice, enabling utilities to enhance infrastructure resilience while leveraging scientific advancements in hazard forecasting and disaster mitigation. Moving forward, strengthening these data-sharing efforts will be key to equipping Oklahoma's rural electric cooperatives with the tools needed to navigate an increasingly complex climate risk landscape.

Data Sharing for Enhanced Power Distribution Resilience and Hazard Mapping

Collaborations between S3OK researchers, working group members, utilities, and wildfire risk mitigation experts has been instrumental in efforts to enhance the resilience of rural electric utilities. One such example from the working

group is [The AI-Enabled Proactive Resilience Enhancement of Electric Infrastructure Against Wildfire](#) project, led by a member of the working group, Dr. Hamid Nazaripouya at Oklahoma State University. This project addresses the critical intersection of wildfires and electrical infrastructure and exemplifies how strategic data sharing and interdisciplinary partnerships are critical to developing actionable risk assessments and resilience strategies for power distribution systems.

Leveraging AI and Data for Proactive Wildfire Resilience

This initiative, initially funded through a one-year S3OK SEED grant, sought to integrate artificial intelligence (AI) and self-healing grid mechanisms to improve power infrastructure resilience under wildfire conditions. By utilizing real-world utility data provided by key partners from the Oklahoma Forestry Services and the Oklahoma Electric Cooperative, researchers were able to:

- Analyze grid vulnerabilities to wildfire ignition, identifying electrical faults that could trigger wildfires.
- Develop a proactive self-healing mechanism, enabling automated fault detection and adaptive restoration to prevent cascading failures.
- Enhance situational awareness for utilities, integrating weather, fuel conditions, and electrical system stress data to predict wildfire risks more accurately.

The project's success led to five publications and secured a \$2.1 million NASA grant, which extends these resilience-focused efforts by incorporating near-real-time wildfire risk assessment and danger rating updates.

Advancing Resilience through Utility Collaboration

The NASA-funded expansion of the AI-enabled resilience project is a key step in developing enhanced products that incorporate dynamic wildfire risk factors. This initiative builds upon

utility data sharing agreements, particularly with OEC, to ensure that the maps provide usable, real-time risk assessments for rural electric utilities. Through partnerships with Oklahoma Forestry Services and OEC, along with regional and national collaborators such as Southern California Edison, USDA Forest Service, and CAL FIRE, the project will ensure that hazard mapping tools are operationally viable, scientifically robust, and directly applicable to rural power grid management.

Impact on Rural Utilities and Future Directions

By leveraging utility-provided electrical infrastructure data and wildfire risk modeling, this initiative is poised to:

- Improve proactive risk assessment by incorporating real-time grid conditions into analysis.
- Enhance decision-making for rural utilities, equipping them with AI-driven insights for grid resilience planning.
- Reduce wildfire ignition risks associated with electrical faults, thereby protecting critical infrastructure and communities.

This collaborative approach underscores the importance of data-sharing agreements between researchers, utilities, and emergency response agencies. By continuing to refine hazard mapping methodologies and integrating cutting-edge AI-driven predictive analytics, the project will provide rural electric utilities with the tools needed to enhance grid resilience and mitigate the increasing wildfire threats in Oklahoma.

Mutually Beneficial Collaborations with Utility Partners

Utilities today face unprecedented challenges in building resilient and economically viable infrastructure amidst increasingly chaotic natural disasters, aging systems, and shifting consumer demands. These challenges are compounded by limited resources, including workforce and financial constraints, which often hinder access to the advanced technical expertise necessary

to address long-term issues. By fostering mutually beneficial collaborations with academic institutions, utilities can unlock innovative solutions that address these challenges while also advancing research that benefits the industry and societal function as a whole. This working group demonstrates **The Value of Collaboration Between Utilities and Academia** and how such

collaborations can be leveraged to enhance **Reliability in Power Grid Resilience**. Combined, these efforts underscore the critical role of utility data sharing in facilitating such partnerships and highlight how leveraging research infrastructure in academia can provide valuable insights and actionable solutions for utility stakeholders.

The Value of Collaboration Between Utilities and Academia

The S3OK project and efforts advanced under the Natural Hazards & Utility Resilience working group demonstrate the potential of such collaborations. During the severe **ice storms of late 2020 and early 2021**, which strained Oklahoma's power grid, researchers worked closely with **Oklahoma Electric Cooperative (OEC)** to analyze grid failures and recovery efforts. By sharing **critical utility data**, OEC enabled researchers to assess **infrastructure resilience, component stresses, and system recovery processes**. This partnership not only yielded **data-driven recommendations** for improving grid reliability but also provided a model for **cost-effective, mutually beneficial collaborations** between academia and utilities. These efforts demonstrate how **data sharing and joint research initiatives** can enhance **operational standards, analytical methods, and long-range infrastructure planning**, helping utilities prepare for **increasingly volatile weather patterns** and the **growing integration of renewable energy**. This collaboration also helped spur new offshoot projects funded by the NSF (e.g., CAREER and Department of Energy awards) that study other aspects of grid resiliency and reliability, such as the impacts of chaotic electromagnetic transients.

A Path Forward for Data Sharing

Building on the success of these collaborations, new opportunities exist for utilities to work with academic researchers on shared challenges in grid resilience and modernization: These include:

- **Long-range infrastructure planning** to mitigate risks from extreme weather and climate variability.
- **Performance optimization** through improved operational standards and system monitoring.
- **Event-based analysis** of grid disturbances, component failures, and service restoration strategies.

By sharing anonymized network data, historical load trends, asset management documentation, and event-specific damage reports, utilities can empower researchers to uncover actionable insights that enhance grid stability and efficiency. Access to maintenance records, Supervisory Control and Data Acquisition (SCADA) logs, and supervised site visits during significant disruptions can further strengthen this research, ensuring that academic findings translate into practical, real-world applications. The results of this project are also being promulgated through the Oklahoma Association of Electric Cooperatives (OAEC) and nationwide entities including the National Rural Electric Cooperative Association (NRECA). OEC has strong representation in these organizations and is advocating for further data sharing from members to support ongoing and offshoot projects.

Reliability in Power Grid Resilience: A Collaborative Approach

Ensuring that power distribution systems are resilient and reliable is an essential challenge for utility providers, particularly in rural communities susceptible to progressive wildfires. As part of a seed grant project funded through S3OK, working group member Dr. Hamid Nazaripouya collaborated with the Oklahoma Association of Electric Cooperatives (OAEC) to examine the distribution of power outages across multiple rural areas in Oklahoma. This partnership provided a data-driven approach to understanding how power disruptions affect different communities and how utilities can enhance resilience while addressing disparities in service reliability.

Assessing the Distribution of Power Outages

Through this collaboration, OAEC provided multi-year power outage data covering several counties within its members' service territories. Researchers analyzed power disruptions over a two-year period, focusing on both major disaster-related outages and routine daily service interruptions. The study assessed key metrics of outage distribution, including:

- Total outage duration across different counties and communities.
- The frequency of outages and their geographic distribution.
- The number of customers affected per outage event.

To identify potential disparities, these metrics were correlated with socioeconomic indicators such as poverty rates, levels of unemployment, racial and ethnic demographics, disability status, and the proportion of senior citizens within affected communities. The findings provided critical insights into how different groups experience power outages and how utilities can better prioritize resources for expedient service restoration.

Advancing Research and Practical Solutions

The results of this study were published in the *Proceedings of the IEEE Power & Energy Society General Meeting*³⁰ highlighting the intersection of power grid resilience and socioeconomic disadvantage. This research underscores the importance of utility-academic collaborations in advancing:

- Data-driven strategies to mitigate imbalances in power restoration efforts.
- More resilient infrastructure planning that considers community needs.
- Proactive solutions to ensure reliable access to electricity, especially in disaster-prone regions.

By fostering partnerships such as the ones described, utilities can leverage research expertise to enhance both operational efficiency and reliability, ensuring that all communities have access to a resilient and dependable power supply. Through open data exchanges and joint research initiatives, utilities and academia can work together to develop smarter, more adaptive power systems capable of withstanding future

challenges. It also enables research findings to influence utility standards and update energy policies focusing on infrastructure planning and resiliency. Moreover, these collaborations not only strengthen infrastructure resilience but also create a foundation for innovative strategies that meet the demands of a rapidly changing energy landscape.

Broadening the Infrastructure Conversation Beyond S30K: Interdependencies, Emerging Technologies, and Transportation Resilience

The need for effective collaborations around natural hazards and utility resilience has never been greater. The challenges ahead demand not only technical innovation but also sustained engagement among researchers, industry professionals, policymakers, and community stakeholders. Moving forward, successful resilience efforts will require a shift from reactive responses to proactive, data-driven strategies that integrate emerging research, real-world expertise, and cross-sector partnerships.

This section delineates critical pathways for future research and engagement around natural hazards and utility resilience. In particular, we highlight the importance of integration of other infrastructure considerations, sustained stakeholder involvement, and emerging technologies and renewable energy sources. We also detail insights for future collaborations gained from our work with a broad range of stakeholders. Finally, in response to the quickly changing risk landscape and in line with utility stakeholder concerns, we address the value of future foci on adopting novel financial tools for utility resilience.

Integrating Other Infrastructure and Considering Cascading Impacts

The increasing interdependence between critical infrastructure systems, such as electricity and transportation networks, presents both opportunities and challenges for resilience planning in the face of natural and human-made disasters. As modern advancements in energy and mobility, including transportation electrification, connected and autonomous transportation, and intelligent traffic management systems,

become more prevalent, their reliance on stable power grids and distribution networks grows. Simultaneously, the electric utility sector depends on transportation systems for fuel delivery, supply chain operations, and maintenance logistics. This intricate web of dependencies introduces new vulnerabilities, particularly in the face of natural hazards and extreme weather events.

A key challenge is the cascading nature of damage, where disruptions in one system ripple through interconnected infrastructure, exacerbating failures and complicating recovery efforts. Understanding how these interdependent systems respond to disasters, the nature of their coupling (tight or loose), and the influence of changing climate conditions remains a crucial research frontier. In addition, research must address the uncertainties in operations and supply-demand imbalances that emerge during extreme events, which can create unforeseen bottlenecks in both power and transportation networks. The extremely long lead times in the order of decades for planning and commissioning transmission and generation capacity to serve new consumer growth is a significant challenge. As a result, existing substations are quickly saturated beyond their capacity resulting in accelerated aging and loss of service life of vital components such as transformers. Better management of consumer loads, including coordinated EV charging, and customer demand response programs will be key in managing the limited resources, especially during extreme weather events and natural hazards.

Beyond the technical vulnerabilities of these interdependencies, the societal dimensions of infrastructure resilience must also be a focal point for future research. As new technologies are deployed, ensuring access to resources during disasters is essential. Climate-driven disruptions occur differentially across communities, raising questions about the fair distribution of energy, mobility, and emergency response capabilities. Research into the social and policy dimensions of resilience will be key to developing inclusive solutions that prioritize community needs alongside technological advancements.

Understanding these dynamics informs **future research priorities** along the lines of:

- **Cascading Infrastructure Failures**
- **Integrating Emerging Technologies**
- **Access in Disaster Response**

Regarding cascading infrastructure failures, investigating how disruptions propagate across interdependent systems and developing predictive models to mitigate widespread failures will be important. Similarly, incorporating non-stationary climate projections into power grid and transportation network planning to improve adaptability to future conditions can enhance the design of climate-resilience infrastructure. Meanwhile, assessing how advancements in electric vehicles, smart grids, and automation affect resilience and system vulnerabilities during disaster unfold will facilitate seamless integration of emerging technologies into analysis, generating relevant research well into the future.

Addressing these critical pathways will strengthen the foundation for interdisciplinary collaborations within the S3OK initiative and beyond, ensuring that research not only advances scientific understanding but also informs real-world infrastructure resilience strategies in an era of increasing climate uncertainty.

Considering Impacts of Emerging Technology and Renewable Energy Sources

As renewable energy adoption accelerates and advanced energy technologies reshape distribution grids, ensuring grid resilience amid natural hazards remains a pressing challenge. Oklahoma, with its high solar potential and significant wind energy infrastructure, is at the forefront of this transition, with over 42% of its electricity generated by wind power in 2023³¹. Additionally, the growth of Distributed Energy Resources (DERs)—such as localized photovoltaic (PV) systems and battery energy storage—is enhancing grid flexibility and reliability and helping overcome bottlenecks in generation and transmission capacity. However, these advancements introduce new technical and

operational challenges that require further research to ensure a stable, climate-resilient energy system.

For example, Distributed PV systems have proven valuable during extreme weather events, such as the 2020 Oklahoma ice storm, by supporting critical loads and expediting recovery. However, their integration presents challenges related to voltage stability, thermal capacity management, and protection coordination. Research on PV Hosting Capacity (PVHC)—the maximum amount of PV a distribution feeder can accommodate without disrupting grid operations—has provided insights into grid constraints, but further investigation is needed to optimize PV placement and adaptive grid management. Future studies should explore:

- Advanced voltage regulation strategies to maintain grid reliability amid fluctuating solar generation.
- Adaptive thermal capacity management for more efficient DER integration.
- Enhanced protection coordination schemes to prevent inverter-based faults from propagating through the grid.

Moreover, the widespread deployment of EV charging stations—both stationary and dynamic wireless charging (DWC)—adds another layer of complexity to power distribution networks. While EVs and DWC technology offer a promising path toward sustainable transportation, they introduce variable loads, voltage fluctuations, and new fault current dynamics that can strain distribution grids. Research has demonstrated the importance of adaptive protection schemes to manage these impacts, but additional work is needed to:

- Develop real-time monitoring and control mechanisms to balance EV demand and grid stability.
- Enhance fault detection and response for EV-integrated networks.
- Explore the role of distributed PV and battery storage in mitigating peak demand from EV charging.

- Enable seamless DER fed microgrids serving communities when existing transmission and distribution networks are experiencing disruptions.

As climate-driven hazards such as severe storms, heatwaves, and wildfires become more frequent, leveraging DERs like PV and battery energy storage systems (BESS) for grid stabilization is crucial. Modeling efforts using real-world distribution feeder data from the Oklahoma Electric Cooperative (OEC) have shown that strategically placed PV-BESS combinations can help smooth demand spikes, optimize renewable energy use, and ensure voltage stability. Future research can support grid resilience by:

- Developing intelligent DER deployment strategies to enhance resilience across varied weather conditions.
- Improving grid flexibility through AI-driven load forecasting and real-time energy management.
- Exploring multi-sector energy coordination to enhance infrastructure resilience during disaster scenarios.

Strengthening Transportation-Grid Interdependencies

The transportation sector is undergoing a rapid transformation, driven by emerging technologies, renewable energy integration, and data-driven innovations. As electric vehicles (EVs), autonomous systems, and renewable

fuels such as solar, green hydrogen, and biofuels reshape mobility, ensuring resilience in these evolving networks is critical. This transformation requires a holistic approach to infrastructure planning that considers robustness, redundancy, rapidity, and resource availability to maintain seamless operations in the face of climate change, natural disasters, and growing energy demands. The integration of EV infrastructure with renewable energy grids has the potential to create decentralized and adaptable systems that enhance energy security and reduce dependence on fossil fuels. However, the growing interdependencies between transportation and energy networks introduce new risks of cascading failures during extreme weather events or cyberattacks. Research must focus on:

- Developing adaptive energy-transportation models that account for disruptions across interlinked systems.
- Assessing cascading failure of risks and identifying strategies to minimize system-wide outages.
- Optimizing EV-grid interaction to balance charging demand with variable renewable energy generation.

Technologies such as wireless charging, autonomous vehicle systems, and predictive analytics improve transportation system efficiency and resilience. The adoption of Internet of Things (IoT) sensors and Artificial Intelligence (AI) facilitates real-time monitoring, predictive

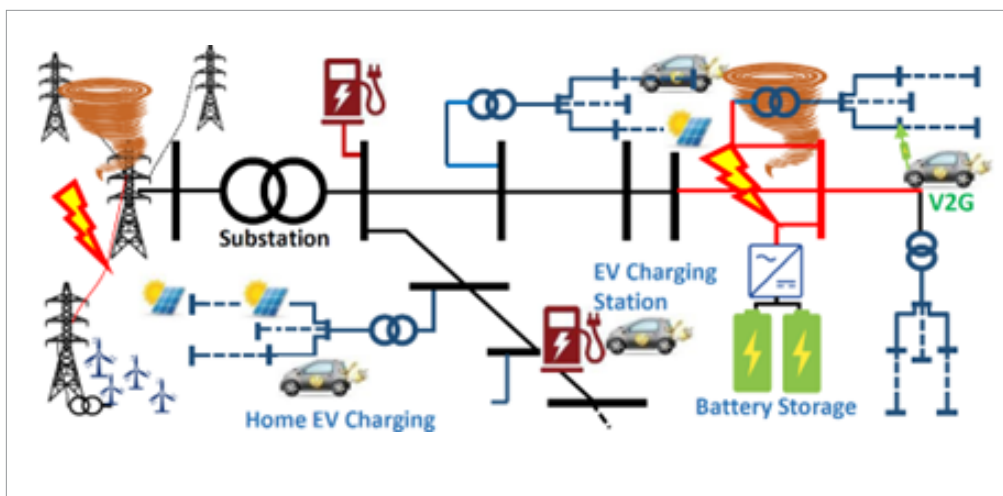


Figure 9.10: Evolving distribution system (Image Source: Panchalogaran and Moses, 2024)²¹

maintenance, and rapid response to infrastructure disruptions. However, to fully harness these advancements, future research should explore:

- Enhancing real-time mobility forecasting for disaster-prone areas using AI-driven models.
- Improving predictive maintenance systems to address infrastructure vulnerabilities preemptively.
- Integrating IoT and AI solutions to optimize traffic flow and emergency response during extreme weather.

As new transportation and energy technologies emerge, ensuring access is essential to prevent widening disparities. Underserved communities often face barriers to adopting EV infrastructure, renewable fuels, and smart mobility solutions due to high costs, geographic distribution gaps, and policy constraints. Additionally, policy and regulatory frameworks have yet to fully address the long-term resilience of these systems under evolving climate and disaster scenarios. Future research should prioritize:

- Developing deployment strategies to ensure that underserved communities benefit from emerging technologies.
- Assessing long-term performance and sustainability of renewable fuels in transportation networks.
- Creating policy frameworks that support resilient transportation-energy systems and ensure regulatory adaptability to technological advancements.

The intersection of transportation, energy, and climate resilience demands collaborative, interdisciplinary research to address emerging vulnerabilities while maximizing the benefits of technological innovation. Moving forward with lessons learned, S3OK affiliates can play a crucial role in bridging engineering and policy considerations to create resilient, sustainable, and inclusive mobility systems.

Adopting Novel Financial Tools for Utility Resilience

As climate-driven disasters become more frequent and severe, the financial burden of disaster recovery and resilience investments is growing, straining traditional public funding mechanisms. To address this challenge, novel financial tools, such as catastrophe bonds (CAT bonds), are emerging as viable alternatives for managing catastrophe risk and financing resilience projects. The integration of these financial instruments into infrastructure resilience planning presents critical opportunities for research and collaboration, particularly in leveraging private capital to support infrastructure adaptation.

Alternative Financial Tools for Disaster Risk Reduction

A key research priority for future work in this area is developing and refining financial models that effectively assess, price, and manage multi-peril catastrophe risks. As part of the S3OK project, researchers have created a high-resolution methodology for quantifying financial losses from natural hazards, with application to pricing CAT bonds, laying the groundwork for integrating financial risk assessment with engineering and climate science models³². Future research should build upon these efforts and focus on:

- Expanding financial risk modeling to incorporate more localized hazard data and infrastructure fragility assessments.
- Enhancing machine learning applications for predicting risk exposure and improving CAT bond pricing accuracy.
- Explore new financial instruments that align with evolving resilience and adaptation needs.

Reducing the Cost of Catastrophe Insurance for Utilities

Electric utilities across the country are facing soaring catastrophe insurance premiums, particularly for wildfire risk, making coverage increasingly unaffordable. This growing financial

strain highlights the need for alternative risk transfer mechanisms that can stabilize costs while maintaining adequate protection. Future research should explore:

- The viability of CAT bonds and other financial innovations in reducing insurance costs for high-risk energy infrastructure.
- New risk-sharing models that distribute financial responsibility across utilities, private investors, and public institutions.
- Policy and regulatory adaptations that facilitate the adoption of CAT bonds and private capital solutions for utility resilience.

Integrating Financial and Engineering Models for Resilient Infrastructure

Ensuring that financial tools effectively support real-world resilience efforts requires closer integration of risk financing with infrastructure adaptation strategies. This includes developing prototypes that combine financial risk models with engineering solutions, enabling utilities to make data-driven investment decisions. Key research pathways include:

Exploring the role of AI-driven catastrophe modeling in linking financial planning with resilience strategies.

Developing frameworks for utilities to integrate financial risk management into resilience planning.

Assessing the effectiveness of CAT bonds in incentivizing long-term infrastructure investments.

A Collaborative Approach to Financing Resilience

The increasing financial risks associated with climate-driven disasters demand an interdisciplinary and multistakeholder approach that brings together financial experts, engineers, policymakers, and climate scientists. Future research collaborations within S3OK affiliates can bridge the gap between infrastructure resilience and financial innovation, ensuring that utilities, investors, and regulators have access to sustainable, scalable solutions for catastrophe risk management.

What Are Catastrophe Bonds (CAT Bonds)?

CAT bonds are a financial tool that allows utilities to transfer risk from natural disasters—like wildfires or ice storms—to investors.

How They Work: Utilities pay premiums to issue bonds. If a predefined disaster (like a wildfire exceeding a certain scale) occurs, bondholders absorb the financial loss, not the utility.

Why It's Useful: CAT bonds can reduce insurance costs and provide faster access to recovery funds.

Relevance to Oklahoma: With increasing wildfire threats and insurance challenges, CAT bonds offer a scalable, market-based resilience strategy—especially for rural co-ops facing growing liability.

Coupling financial modeling with climate science can help utilities prepare for and withstand high-impact, low-probability events.

Navigating Compound Events: Addressing Emergent Risks in Utility Resilience

Rising temperatures, shifting precipitation patterns, and increasing flash drought frequency are intensifying wildfire risks and straining Oklahoma's utility infrastructure. By 2050, the state could see up to 30 more days above 100°F annually, while the eastward migration of the climatological dry line will likely heighten drought and wildfire threats in the near term across the Central Great Plains³³. As population growth and energy demand rise, grid resilience must move beyond historical baselines to account for non-stationary climate risks in infrastructure planning and management.

A major challenge is the predictability gap on S2S timescales, limiting early warnings for extreme weather. Improving S2S forecasting will be critical for stakeholders such as utility managers, emergency planners, and policymakers, as well as citizens who would benefit from being able to anticipate risks and allocate resources effectively. Additionally, compound events—instances in which multiple extremes such as heatwaves, wildfires, or ice storms occur back-to-back or at once—present unique grid stressors across the region. These events are expected to become more frequent in the future^{34–37} and increase infrastructure vulnerabilities and disrupt response efforts beyond what is observed with individual extreme events. In particular, compound events have the potential to generate greater impacts by decreasing time for recovery and restoration efforts between events or overwhelming human and utility systems through simultaneous occurrence. In light of the unique challenges posed by compound events, future collaborations should focus on:

- **Improving S2S Forecasting** – Closing the predictability gap to support proactive decision-making.
- **Incorporating Climate Projections into Grid Planning** – Moving beyond historical trends to account for evolving risks.
- **Developing Strategies for Compound Events** – Understanding cascading impacts and refining response measures.
- **Strengthening Utility–Research Partnerships** – Co-producing solutions tailored to real-world operational needs.

By integrating advanced forecasting, climate-adaptive planning, and cross-sector collaboration, stakeholders can better prepare for future extreme weather challenges and build a more resilient energy system.

Insights for Future Collaborations

Through the research collaborations described in this chapter, we have identified key insights that can inform and strengthen future collaborations between researchers and utility practitioners.

This section distills the lessons learned from our engagements, highlighting strategies for fostering effective partnerships, addressing barriers to collaboration, and enhancing the integration of scientific research into decision-making processes. By reflecting on our experiences, we offer guidance for designing collaborative efforts that are both responsive to emerging challenges and grounded in long-term resilience planning.

Building Resilience through Collaboration: Lessons Learned for Future Partnerships

Effective resilience research requires both interdisciplinary expertise and sustained stakeholder engagement. [The Seed Grant project awarded to working group member Dr. Hamid Nazaripouya](#) exemplifies this approach. Initially focused on a technical challenge related to power grid resilience amid wildfires, the project quickly expanded beyond electrical engineering in response to the recognition that addressing wildfire risks required a broader perspective. By integrating expertise from Geography, Fire Safety & Protection, Ecology, and Industrial Engineering, the team developed a more comprehensive approach to wildfire impact mitigation.

Beyond academia, these multi-stakeholder collaborations ensure that research findings are both analytically rigorous and practically applicable. In the collaboration here, partners provided operational data while facilitating real-world implementation, bridging the gap between research and practice.

What began as a technical research project evolved into a multi-sector research network, fostering long-term academic-industry collaboration, joint proposals, and publications. This case highlights the importance of flexibility, cross-disciplinary engagement, and sustained partnerships in addressing complex environmental challenges, offering a model for future collaborations in resilience research. In particular, looking across collaborations central to the Natural Hazard and Utility Resilience working group, we suggest future collaborations:

1. **Embrace Interdisciplinary Expertise** – Complex challenges like wildfire resilience require perspectives beyond a single discipline. Integrating a range of fields such as environmental science, engineering, and public policy enhances the depth and applicability of research.
2. **Engage Stakeholders Early and Continuously** – Building relationships with industry partners, government agencies, and community organizations from the outset ensures that research is aligned with real-world needs and facilitates smoother implementation.
3. **Bridge Research and Practice** – Collaborations should prioritize not only theoretical advancements but also practical applications, leveraging operational data and real-world insights to create actionable solutions.
4. **Foster Long-Term Partnerships** – Moving beyond short-term projects to sustained collaborations strengthens institutional capacity, facilitates joint funding opportunities, and expands the impact of research efforts.
5. **Maintain Flexibility and Adaptability** – The ability to pivot in response to emerging challenges or new insights is critical for tackling complex infrastructure problems and ensuring research remains relevant and effective.

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Water Availability Challenges and the Regulatory Environment Deep Dive

Introduction and Overview

Throughout the S3OK project, OLAN members have identified that projects designed to address water-related challenges that frequently intersect with the regulatory environment. To better understand OLAN perceptions and experiences regarding the role of regulation in this domain, and in an effort to be mindful of these dynamics as scientists work towards technical solutions around water treatment, conservation, storage, and/or re-use, S3OK researchers organized a deep dive discussion to obtain further OLAN insights. On April 6th, 2023, members of the OLAN met with S3OK scientists to discuss water availability and regulation in a wide-ranging conversation. **A full analysis of this deep dive conversation will be complete by Fall 2023.**

Water Availability Challenges and their Intersection with the Regulatory Environment

Meeting participants articulated that a successful approach to water availability problems in Oklahoma requires **balancing regulatory frameworks and mandates with incentives to promote compliance**. While in many cases water systems managers rely on mandates for water conservation and efficiency, inconsistent enforcement can reduce compliance. Participants noted that **effectiveness of mandates alone is often unreliable** and in some cases counter-productive to the desired outcomes. Instead, it may be more effective to **use incentives, including negative incentives**, such as drought pricing, **to encourage conservation**. To strike a balance, participants pointed to their experiences with a layered approach that includes incentives, negative incentives, regulations, and enforcement, all utilized in tandem to achieve desired outcomes. Deep dive participants did note an exception to this layered approach, for matters of public safety, focusing on potable water re-use projects as they relate to drinking water standards. In this case, participants referenced the significant statutory and regulatory requirements already in place, and discussed the need for enforcement to ensure adherence to these requirements.

Allowing for Innovations in the Regulatory Process

The regulatory process provides challenges and opportunities that accompany the innovations needed to achieve Oklahoma's water goals. Participants noted that regulations are typically designed to be specific and prescriptive, which may not allow for the flexibility needed to accommodate individual water re-use options. **Every community has unique needs and circumstances** under which they pursue conservation or re-use programs. **The challenge for regulatory bodies is to balance flexibility and specificity while working to meet the needs of all communities**. To address this challenge, deep dive participants discussed the potential for a **performance-based process to regulation that specifies the set of pre-authorized technologies but also allows flexibility in applying different technologies as long as they achieve the agreed-upon objectives as long as they achieve the agreed-upon objective**. This provides regulators an opportunity to approve new and innovative technologies that are not specifically delineated within existing standards.



Water Availability Challenges and the Regulatory Environment Deep Dive

Drawing Inspiration for Regulatory Trends Across the Country

Deep dive participants identified several key points regarding both regulatory and non-regulatory development trends outside of Oklahoma. Points discussed included:

- **consideration of cost-sharing for water projects**, as seen in North Dakota, where the state invests \$200-\$300 million per year into water projects.
- **incentivizing good water management practices** such as leak detection programs is important.
- the potential for **regionalization as a solution**, so long as there are strong efforts to maintain **autonomy**. Moreover, **emergency connections between regions can provide resiliency and redundancy** in current water systems planning and in prospective regionalization plans.

Toward Actionable Guidance and Next Steps

Participants discussed both regulatory and non-regulatory actions that advance water conservation efforts. They noted that not only do regulatory bodies enforce codes and rules that include areas such as water permits for use, well drilling, and permissible end uses for water re-use projects, but they also oversee and partner with voluntary programs designed to increase water availability. These include voluntary water audit programs, water use reporting, and financial assistance for water projects.

Deep dive participants also discussed water loss challenges, which can be as high as 80% in some systems. While some states have mandatory water loss auditing, Oklahoma only has a voluntary program. To address this gap, participants discussed ways that larger systems can help smaller nearby systems to **augment water loss auditing with better outreach and education to water systems managers**.

In light of observations and suggestions made during this deep dive conversation, S3OK scientists will initiate conversations regarding how the insights from their research focused on water reuse and conservation can be successfully integrating into the existing regulatory landscape. Establishing a viable path forward for sustainable science-informed solutions to these challenges is necessary, as regulatory solutions are considered in concert with other approaches. OLAN insights from the deep dive conversations are instrumental to the S3OK project and will continue to shape the project. Additional opportunities for engagement between scientists and OLAN members are available to continue to conversation. **To see a list of scheduled, upcoming deep dive conversations on other cross-cutting topics, and express interest in attending, scan the QR Code.**



Extreme Weather and Oklahoma Infrastructure Interactions (Wildfire Focus)

Introduction and Overview

Throughout the S3OK project and particularly at the May 2022 S3OK Academy meeting, Opinion Leader Advisory Network (OLAN) members emphasized the need to develop cross-cutting understanding and approaches to wildfire measurement, planning, and mitigation in the context of infrastructure in Oklahoma. Amidst S3OK advancements toward sustainable solutions to Oklahoma's wicked problems, OLAN members have also noted the need for differentiated approaches to this issue in response to Oklahoma's diverse landscape, an interest/need for public understanding and engagement, and have expressed interest in the development of new decision-making tools. In response to this feedback, S3OK researchers organized a Deep Dive discussion to obtain further OLAN insights on this cross-cutting topic, and on July 27th, 2023, members of the OLAN met with S3OK scientists to discuss these challenges. **A full analysis of this Deep Dive conversation will be complete by Fall 2023.**

Understanding Wildfires and Wildfire Catalysts

This Deep Dive conversation allowed participants to expand upon the intersection of severe weather and electric infrastructure risks identified through previous S3OK discussions. Though topically oriented around wildfire and infrastructure concerns, many deep dive participants drew upon first-hand experience with challenges associated with ice and electric infrastructure in discussion. Even so, deep dive participants identified a variety of primary triggers for wildfire that include pole breakage influenced by wind direction as well as broader exacerbating factors rooted in severe weather. This included high winds, extreme heat, and drought, each of which impact various landscapes. Additionally, participants stressed that vegetation type impacts fire behavior alongside land cover, crucial for path prediction. Moreover, attendees noted that as Oklahoma's urban landscape expands, the threat of wildfire hinges on urban-rural boundary transformations, which can intensify wildfire severity. This, coupled with vegetation and geography, elevates wildfire complexity amid changing landscapes and encroaching settlements, which calls for careful deployment of resources and knowledge across a variety of sectors to mitigate wildfire risks.

Planning and Mitigation

During the meeting, Deep Dive participants discussed a number of specific factors that must be taken into account for effective wildfire planning and mitigation. These include **leveraging data and forecasting in wildfire planning and mitigation** by analyzing historical data to identify patterns and trends in events that can create the conditions for wildfires—such as lightning, ice storms, and drought. These data can help planners understand the likelihood of these events happening in the future. Meanwhile, **mid-range forecasting** that provide insights several weeks to several months out can help practitioners better communicate changing frequencies and intensities of weather events to landowners and planners seeking to mitigate wildfire risks. In order to effectively leverage data and utilize forecasting in wildfire measurement, planning, and mitigation, discussion participants underscored the need **for data sharing across agencies and institutions**, including utilities and researchers. In particular, attendees emphasized the value of crafting decision-making tools through experience-informed modeling, highlighting the pivotal role of data-driven insights in effective decision-making and risk mitigation across diverse weather events. In the case of wildfire risk, participants stressed the importance of translating complex data into actionable information for an array of stakeholders, from local authorities to government officials, underscoring the need for **tailored data approaches** based on specific scenarios. In short, Deep Dive attendees emphasized the value of collaboration, tailored data analysis, effective communication, and the practical application of research findings in empowering decision-makers across sectors.

Risk Assessment and Design Standards

Discussion participants also emphasized crucial components within utility operations that should be considered in the approach to risk assessment and design standards. Primarily, they noted **adherence to industry-specific design standards** as a cornerstone, as these standards account for diverse factors, encompassing wind speed, ice loading, and prevailing environmental conditions; current infrastructure systems are not often built beyond these design standards. As a result, justification for infrastructure design exceeding industry standards would need to be clear, compelling, and demonstrate that designing to the standard is not adequate in the context of contemporary risks. In parallel, discussion participants called for a **rigorous risk assessment** process to be undertaken. In some cases, electric utility service providers undertake risk assessment of their service region. However, there is a need for a comprehensive and standardized approach to risk assessment across the state. This assessment could encompass an evaluation of vulnerabilities linked to a spectrum of weather-related phenomena, ranging from ice storms to wildfires. Insights garnered from these evaluations would then guide the allocation of resources necessary for fortifying infrastructure resilience effectively across multiple threats. To this point, discussion participants also emphasized **the role of insurance industry influence** in this context, as the insurance industry is influential in establishing a baseline for risk. Moreover, their willingness to provide coverage for specific projects can influence decisions related to investment in infrastructure. Taken together, each of these factors undergird long term planning for infrastructure projects and can guide resilience-oriented research and investment in infrastructure. In particular, S3OK researchers can leverage enhanced modeling and risk analysis to make recommendations across utility service areas.

A Context Appropriate Approach

Throughout the conversation, Deep Dive participants called attention to the need to **adopt a context-appropriate approach to wildfire mitigation planning**. Within the Oklahoma context, an evolving energy mix emerged in conversation as utilities navigate the integration of renewables such as wind and solar into their generation mix. Relatedly, participants articulated challenges related to grid stability, particularly concerning the incorporation of distributed solar installations and the substantial obstacles posed by a diverse energy infrastructure landscape that includes multiple utility service jurisdictions. Furthermore, discussion participants emphasized how attuned to environmental dynamics landowners, planners, and researchers are. This is particularly acute regarding the intersection of vegetation management and utility infrastructure. For example, tree trimming and clearance maintenance is paramount in mitigating wildfire risks, but reveals challenging tensions between utility operators and landowners seeking to mitigate wildfire risk while balancing respect for individual landscape attachment and the potential negative impacts from extreme weather events on energy systems and communities.

Next Steps

In light of observations and suggestions made during this Deep Dive conversation, S3OK scientists will initiate conversations regarding how the insights from their research can be tailored to meet the diverse needs of practitioners at the intersection of wildfire and infrastructure planning. Identifying a viable and scalable set of solutions to the challenges that exist in this domain is urgent, given the increasing threat of wildfire for infrastructure and society in Oklahoma. OLAN insights from this and other Deep Dive conversations are instrumental to shaping the direction of the S3OK project, and additional opportunities for engagement between scientists and OLAN members are being planned in order to continue the conversation.



Implementing Land Management Strategies for Water Use Efficiency in the Context of Agricultural Systems

Introduction and Overview

Throughout the S3OK project and particularly at the May 2022 S3OK Academy meeting, Advisory Network (OLAN) members have underscored the need to implement land management strategies for water use efficiency in the context of agricultural systems in Oklahoma. Amidst S3OK advancements toward sustainable solutions to Oklahoma's wicked problems, OLAN members have also noted the unique challenges small producers and landowners face when addressing changing seasonal to subseasonal weather patterns, implementing new technologies and strategies, and integrating forecasting tools into decision making processes. In response to this feedback, S3OK researchers organized a Deep Dive conversation to obtain further OLAN insights on this cross-cutting topic, and on July 18th, 2023, members of the OLAN met with S3OK scientists to discuss these challenges. **A full analysis of this Deep Dive conversation will be complete by Fall 2023.**

Beyond Eastern Red Cedar Encroachment

At the start of the discussion, participants affirmed that the current S3OK outline of prospective solutions for land management and water efficiency challenges—including eastern red cedar removal and vegetation management—accurately reflects this problem domain as they understand it. However, as the conversation continued, participants suggested the expansion of this outline to include solution pathways beyond Eastern Red Cedar Encroachment. For example, participants suggested the S3OK project explore solution pathways that involve **strategic feed mix changes in livestock farms**. Substantive area experts noted the potential impact of changing the mix of feed for livestock as an additional aspect or auxiliary approach to enhancing water efficiency in land management. Additionally, participants discussed the importance of **wildfire management plans**. Participants noted the interconnectedness between wildfires, vegetation and water; in dry conditions, vegetation can fuel wildfire, which in turn may impact the quantity and quality of available water sources. Addressing vegetation status, wildfire risk, and the potential impact on water quantity and quality could be an important consideration within the scope of water-efficient land management practices. Similarly, participants encouraged research teams working at the intersection of land management and water to consider **regional customization of recommended practices**. Attendees highlighted that the trade-offs and benefits of various land management practices are dependent on the specific geographical region, underscoring the importance of customizing strategies based on the natural geography and conditions of an area. For example, afforestation or tree planting with consideration to carbon sequestration and water use must be carefully evaluated and tailored to the specific water availability and demands of different regions.

Scalable Solutions for Small Producers

An additional key observation at this Deep Dive addressed the particular complexities for smaller landowners and producers when they consider implementing new technologies and approaches. Yet while challenges exist, participants noted several efforts that could be made or are currently being made to provide education, resources, and community support to facilitate the adoption of water-efficient practices and technologies among smaller producers and landowners. Participants emphasized the need for easy-to-use and rapidly deployable **cost mitigation or incentive programs** to assist smaller landowners and producers in implementing smart irrigation technologies, which often have large upfront costs.



Implementing Land Management Strategies for Water Use Efficiency in the Context of Agricultural Systems

Scalable Solutions for Small Producers

While effective programs are underway to promote the adoption of these technologies, meeting participants indicated that the up-front financial burden of implementing them, such as installing sensors, can be a barrier for smaller producers. Attendees also underscored the value of **educational initiatives and public perception campaigns** as solution pathways that can address resistance to implementing new technology. In this case, attendees shared their experience with producers who may be resistant to certain technologies or practices. Participants suggested community involvement and collaboration as a driving strategy for the adoption of new technologies and practice, as well as corresponding educational initiatives aimed at helping smaller producers adopt water-efficient practices and new technologies. Finally, discussants touched on the need to connect small landowners with resources and volunteer associations that support sharing new water reuse/efficiency strategies and vegetation management techniques with small landowners.

Forecasting and Decision Making

During the Deep Dive, attendees noted that the utilization of insights from forecasts as inputs into decision-making processes varies across different agricultural contexts and sectors. Farmers and producers consider do forecasts when making choices about planting, irrigation scheduling, and overall management of their operations. However, farmers and producers often rely on historical data and knowledge derived from past experience with long-term weather patterns, and relying solely on historical data may not fully account for changing weather patterns. Participants noted what while forecasting can provide insights into potential shifts in these patterns, there are varying levels of trust in the accuracy and reliability of such forecasts. To account for this, participants suggested more **seamless forecast integration** that incorporates forecast data with irrigation scheduling tools, such as crop models linked to pivots, to help optimize resource use. These tools can make use of predicted weather conditions to estimate water requirements and adjust irrigation rates accordingly, ultimately improving efficiency and reducing resource waste. Similarly, discussions highlighted the value of **enhancing the availability of quality data**. On this front, accurate and up-to-date data on water availability and quality are critical for effective decision-making. Monitoring and measuring water use, nutrient levels, and other environmental factors are vital for understanding trends, assessing impacts, and implementing informed strategies. Data quality, accessibility, and transparency are ongoing concerns in various industries, including agriculture and industrial operations which may have varied attitudes toward monitoring and data collection.

Next Steps

In light of observations and suggestions made during this deep dive conversation, S3OK scientists will initiate conversations regarding how the insights from their research can be successfully scaled and adapted to maintain relevance for small landowners and producers. Establishing a viable path forward for sustainable solutions to these challenges faced by small landowners and producers is necessary, as they are central to providing essential products across Oklahoma. OLAN insights from this and other Deep Dive conversations are instrumental to shaping the direction of the S3OK project, and additional opportunities for engagement between scientists and OLAN members are being planned in order to continue the conversation.

Introduction and Overview

Throughout the S3OK project, Advisory Network (OLAN) members have underscored the diversity of Oklahoma's water systems. Amidst S3OK advancements toward sustainable solutions to Oklahoma's wicked problems, OLAN members have noted the unique challenges small water systems face, including those related to infrastructure maintenance and implementation of new technologies, revenue/funding sources for small system projects, and workforce and training needs. In response to this feedback, S3OK researchers organized a deep dive discussion to obtain further OLAN insights on this cross-cutting topic, and on June 6th, 2023, members of the OLAN met with S3OK scientists to discuss small water systems challenges. **A full analysis of this deep dive conversation will be complete by Fall 2023.**

Future Outlook and the Recruitment and Retention of a Highly Skilled Workforce

Discussion participants identified several common challenges related to human capital, specifically that small water systems face challenges regarding workforce recruitment, retention, and succession planning. For example, one major challenge mentioned by the participants is the common **absence of succession plans for colleagues** despite many small system operators entering retirement age. Additionally, both **cost barriers** and **resistance to implementing new technology** means that some operators have not updated procedures or implemented new technologies like GIS mapping, which could benefit the water system as a whole. Moreover, challenges in **recruiting and retaining a qualified workforce** resulting from low compensation and job desirability was widely acknowledged. To this end, participants highlighted the need to **expand programs to attract and retain qualified personnel**. They argue that these positions, which provide a crucial public health service, are undervalued and underappreciated. The demanding nature of the job, including long hours, on-call duties, and working on holidays, further adds to the challenges of recruitment and retention. Compounding workforce related challenges is the complex and interrelated nature of prospective solutions. Participants noted that many of the problems small water systems and their operators face can be solved with a collaborative approach contingent upon **cohesive coordination across agencies and funding entities**.

Economic Investment in Small Water Systems

Discussion participants acknowledged that limited economic resources across small water systems were central to many of the challenges they faced. Many participants mentioned the resistance to raising rates for water services, as rate increases are perceived negatively and can generate pushback from the public. However, inadequate economic resources make it difficult for small water systems to cover operational expenses and much needed infrastructure upgrades. To address this, participants discussed the value and need to **communicate the long-term economic benefits of investing in water infrastructure** to their communities. Further compounding challenges associated with limited economic resources are fines resulting from non-compliance with regulatory requirements. Participants mentioned instances where systems fail to communicate or engage with regulatory agencies, leading to fines and consent orders. While the reasons for this are varied, in each case these added expenses are avoidable if systems communicate with regulatory agencies and that simultaneously small systems **strive to better understand compliance and regulatory requirements while regulatory agencies increase training and communication opportunities**. One possible, but underutilized, pathway for ameliorating challenges associated with economic resources is to **enhance small water systems' awareness of available funding opportunities**. Some operators do not engage in conversations with agencies like the Department of Environmental Quality (DEQ) and the Oklahoma Water Resources Board (OWRB) due to negative perceptions.

Economic Investment in Small Water Systems (continued)

Enhancing communication, both between agencies with funding available and between agencies and small systems, has the potential to **expand small water systems' ability to access funding and support** for system improvements. Moreover, small water systems can seek to **implement some initial, highly cost-effective improvements** such as subscriptions to mapping tools and increasingly **leverage and combine funding from different sources**, including tribes and state programs.

Aging Infrastructure and Evolving Standards and Practices

Small water systems in Oklahoma are often characterized by aging infrastructure which presents barriers to keeping up with evolving standards and practices. Many of Oklahoma's small water systems were built in the 1960s and are unable to meet the standards of modern regulations which have expanded to include things like PFAS and other contaminants of emerging concern. To assist small water systems in keeping up with these changes, discussion participants highlight the need for organizations like the DEQ **update lists of approved firms that provide services and to reevaluate projects as circumstances change**. Furthermore, there is a need to **revisit and establish best practices to pursue feasible solutions for small water systems**. Discussion participants underscored the need to **establish a repository of successful best practices and feasible solutions implemented by systems of similar size**, to be used as a template or model. Small water systems can look to organizations like the Environmental Protection Agency (EPA) and DEQ for inspiration to **generate a list of best practices, white papers, and implementation guides to support established projects in their systems**. Finally, small water systems may be able to **leverage the suggested economic solutions** including layering funding streams to update infrastructure **to meet current requirements**, including addressing unregulated contaminants. Another prospective solution to the challenges posed by aging infrastructure and evolving standards and practices identified during discussion is **regionalization across small water systems**. However, regionalization must be completed in a way that retains some degree of autonomy for small water systems in the long term. Though attachments to a town's identity and history can lead to resistance to regionalization and prevent communities from accepting external assistance, there is a need to **define regionalization broadly and consider sharing operational resources across small water systems**.

Toward Actionable Guidance and Next Steps

In light of observations and suggestions made during this deep dive conversation, S3OK scientists will initiate conversations regarding how the insights from their research can be successfully scaled and adapted to maintain relevance for small water systems. Establishing a viable path forward for sustainable science-informed solutions to the challenges faced by small water systems is necessary, as these systems are central to providing essential services across Oklahoma. OLAN insights from the deep dive conversations are instrumental to the S3OK project, and interactions between the OLAN and the S3OK science teams will continue to shape the set of solutions being developed by the project. Additional opportunities for engagement between scientists and OLAN members are available to continue the conversation. To see a list of scheduled, upcoming deep dive conversations on other cross-cutting topics, and express interest in attending, scan the QR Code or [click here](#).

Introduction and Overview

Throughout the S3OK project and most recently at the May 2022 S3OK Academy meeting, Advisory Network (OLAN) members have emphasized the importance of stakeholder engagement as the S3OK team seeks sustainable solutions to Oklahoma's wicked problems. In response to this feedback, S3OK researchers organized a deep dive discussion to obtain further OLAN insights on this cross-cutting topic, and on March 23, 2023, members of the OLAN met with S3OK scientists to discuss effective stakeholder engagement strategies and future needs. **A full analysis of this deep dive conversation will be complete by Fall 2023.**

Highlighted Observations

Through robust discussion, deep dive participants developed a shared definition of a stakeholder as **"anyone who is affected by a situation, whether they are involved in or aware of the situation or not."** This definition has significant implications for how stakeholders are considered and engaged. During the discussion, participants referenced this shared definition as they enumerated challenges and barriers to engagement. In the context of these barriers, they also offered specific recommendations for strategies for improved stakeholder engagement.

Identified Barriers to Engagement

- Discussants reflected that in some cases, stakeholders don't consider themselves as such, have limited time and bandwidth, and/or may feel overwhelmed by the quantity of information available.
- Additionally, discussion participants mentioned that while stakeholders want problems solved, they may need help understanding how to make their voices heard or may otherwise feel disenfranchised from the problem-solving process.
- The group noted that stakeholders might be unsure about whose information to trust.
- Several participants noted that Oklahoma's unique historical legacy of engagement with tribal nations and marginalized groups has, in some cases, frayed or exhausted social capital, leading to distrust.

Identified Strategies to Improve Engagement

Participants offered numerous suggestions for improving future engagement within and outside of the project. To address challenges related to limited stakeholder time and bandwidth, participants particularly noted that in order to engage stakeholders effectively, it is important to practice active listening and disseminate information in a way that reaches myriad audiences. Several individuals also referenced that there must be a willingness to provide information and opportunities to **receive stakeholder input proactively, rather than waiting for stakeholders to seek out information**; relatedly, discussants recommended that **we seek new ways to empower all stakeholders to make their voices heard**. One specific recommendation was to use a range of tools for reciprocal and uni-dimensional engagement, such as social media or podcasts.

A promising approach to address skepticism or lack of trust in information could be to **identify, engage with and provide information to stakeholders through trusted individuals who deeply know their communities**.

To address barriers to engagement with groups that have experienced historical marginalization or mistreatment, discussion group participants emphasized the importance of avoiding making assumptions and emphasizing a willingness to compromise. Other specific recommendations for those seeking to engage stakeholders include:

- increasing and maintaining a high level of cultural competence when engaging with impacted groups
- devoting significant time and energy to slowly building/rebuilding trust

Next Steps

In light of observations and suggestions made during this deep dive conversation, the final phase of OLAN membership recruitment will focus on engaging additional under-represented groups and key community voices across the science focus areas. Project leadership will also **seek additional opportunities to externally disseminate project findings to a wider audience**, using new tools for outreach to broaden accessibility and understanding among stakeholders. Science team members will coordinate with OLAN members to ensure project outcomes reach the broadest audience possible.

OLAN insights from the deep dive conversations are instrumental to the S3OK project and are already shaping how the project carries out engagement in the future. **To see a list of scheduled, upcoming deep dive conversations on other cross-cutting topics, and express interest in attending, [click here](#).**

Upcoming project events, such as the Year 3 Academy, will include additional information-sharing mechanisms, including a featured poster session highlighting cross-cutting research with an applied focus, presentations from researchers focusing on OLAN-identified priorities, and an extended listening and feedback session regarding ongoing solution development. To register for the Year 3 Academy, [click here](#). **We look forward to seeing you on May 16th and 17th at the Colcord Hotel in Oklahoma City!**