Research Plan and Gap Analysis for Produced Water Reuse in New Mexico

A Gap Analysis and Research Plan for the Reuse of Produced Water Addressing the Technical, Economic, and Health and Safety Risks of Fit-for-Purpose Reuse

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Executive Summary

This science and technology gap analysis and research plan was prepared by the New Mexico Produced Water Research Consortium in response to the legislative directive of the 2019 Produced Water Act (HB 546) and a subsequent Memorandum of Understanding with the New Mexico Environment Department.[1]

The gap analysis summarizes gaps in knowledge surrounding the technical, economic, human and environmental health and safety issues, and concerns associated with the reuse of treated produced water for fit-for-purpose uses outside the oil and gas sector.

The research plan includes the identification of science and technology research, development, and demonstration efforts needed to fill these gaps. The tasks described herein are intended to provide a system-level understanding to reduce the risks of using treated produced water while protecting socio-economic, environmental, and ecological systems in New Mexico.

The topics addressed in this document include:

- Improved produced water quantity and quality sampling, analysis, and data access;
- Produced water pre-treatment/treatment costs, performance testing, and analysis;
- Toxicity testing standards development and risk analysis;
- Socio-economic, environmental, and ecological cost/benefit analysis;
- Health and safety compliance monitoring of fit-for-purpose applications;
- Regulatory agency cooperation and collaboration;
- Water and energy infrastructure planning and development; and
- Public education and outreach.

[1] 2019 HB 546 – Fluid Oil & Gas Waste Act: https://www.nmlegis.gov/Legislation/Legislation?chamber=H&legType=B&legNo=546&year=19

Acknowledgments

The information presented in this document was informed by discussions and input provided by members of the six Working Groups of the 2020-2021 Technical Steering Committee (TSC) of the New Mexico Produced Water Research Consortium (NMPWRC or Consortium), along with members of the Government Advisory Board (GAB). Valuable information was gained from the review of five public meetings on produced water reuse held from October through November 2019 across New Mexico by the New Mexico Environment Department, with support from the NMPWRC. Also informing the work are reports from the Ground Water Protection Council and the U.S. Environmental Protection Agency. Important information was obtained from New Mexico's current State Energy plan and the 2018 State Water plan, roadmaps, case studies of produced water reuse issues, and approaches from other states. University contributions include technical reports written by researchers at New Mexico State University, the University of New Mexico, and New Mexico Institute of Mining and Technology.

The directions presented herein represent a general understanding of the major challenges, concerns, and priority research and development directions currently needed in New Mexico, as identified by a broad spectrum of industry, consultants, technology providers, academia, nongovernmental organizations (NGOs), federal, state, and local agencies, and natural resource and user association representatives that comprise the Consortium membership.

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Acronyms

ac/ft	acre feet (of water)
bbl	Barrel (42 gallons)
BOR	United States Bureau of Reclamation
BGD	Billion gallons per day
CBM	Coal Bed Methane
DOD	United States Department of Defense
DOE	Department of Energy
EMNRD	New Mexico Energy Minerals and Natural Resources Department
EPA	United States Environmental Protection Agency
ETV	Environmental Technology Verification
FRTR	Federal Remediation Technology Roundtable
GAB	NMPWRC Government Advisory Board
ITRD	Innovative Technology Treatment Demonstration
MGD	Million gallons per day
mg/L	Milligrams per liter
MOU	Memorandum of Understanding
NMED	New Mexico Environment Department
NMPWRC	New Mexico Produced Water Research Consortium
NMSU	New Mexico State University
NORM	Naturally Occurring Radioactive Materials
OCD	New Mexico Oil Conservation Division
O&M	Operation and Maintenance
PFD	Process Flow Diagram
PW	Produced Water
QA/QC	Quality Assurance and Quality Control
SOP	Standard Operating Procedure
TDS	Total Dissolved Solids
TSC	Technical Steering Committee of NMPWRC
USGS	United States Geological Survey
WRAP	Water Reuse Action Plan
WET	Whole Effluent Toxicity
WRRI	New Mexico Water Resources Research Institute

1. Introduction and Purpose

The western United States, including New Mexico, is facing aridification of historical proportions. This means that we should plan for the depletion of traditional fresh water supplies and the subsequent impact on humans, wildlife, and ecosystems.

One way to reduce negative impacts on our fresh water supplies is to substitute treated brackish, saline, impaired, or wastewater as appropriate for use in human, ecological, or industrial applications or processes. Fit-for-purpose reuse refers to the treatment and use of impaired waters to the level of quality required by a specific application and associated regulations. The U.S. Environmental Protection Agency (EPA) has developed a National Water Reuse Action Plan (WRAP, https://www.epa.gov/waterreuse/water-reuse-action-plan) that identifies five major sectors for wastewater reuse, including the use of treated produced water. Industrial processes are prime targets for the use of fit-for-purpose treatment and reuse of wastewater. A well-known example of a substitution is the use of tertiary treated municipal wastewater for golf course and parkland irrigation, instead of using fresh ground water or surface water.

The treatment and reuse of produced water is one of the smaller wastewater reuse sectors in the EPA's Water Reuse Action Plan because oil and gas production does not occur in every state, though there are over 30 states in the US with oil and gas operations. New Mexico is one of the states with large production of oil and gas produced water; and therefore, produced water reuse could be significant in volumetric relation to the state's total water budget in regions where produced water is available. For example, produced water generated in Lea and Eddy counties in 2020 was equivalent to approximately 25% of the total fresh water use in these two counties.

There are opportunities for treated produced water reuse applications both within and outside the oil and gas sector. For example, by 2021 the treatment and reuse of produced water for drilling, fracking, and enhanced oil recovery has reduced the use of fresh water to less than a few percent of all water use in oil and gas operations in New Mexico. However, nationally and in many states, including New Mexico, there are not yet environmental and human health standards and regulatory mechanisms in place to permit and support treated produced water reuse outside of the oil and gas sector. Defining and measuring what is a "safe use" is a critical part of any wastewater reuse process. Therefore, adequate analytical characterization before and after treatment, sufficient health and safety testing, and risk analysis are needed to support the development of appropriate guidance and regulations for the safe use of treated produced water for future fit-for-purpose applications.

Definitions included in 2019 NM HB546:

Produced water -- a fluid that is an incidental byproduct from drilling for, or the production of, oil and gas.

Treated produced water -- water reconditioned by mechanical or chemical processes into a reusable form.

Recycled produced water -- water reconditioned by a recycling facility permitted by the Oil Conservation Division of the Energy, Minerals and Natural Resources Department (EMNRD)

The New Mexico legislature has addressed the possibility that treated produced water could be useful as a supplemental water resource under certain conditions. In 2019, the New Mexico State Legislature passed House Bill 546, which includes the Produced Water Act. The bill amended portions of the Water Quality Act (NMSA 1978, Sections 74-6-1 to -17) directing the Water Quality Control Commission to adopt regulations for "the discharge, handling, transport, storage, recycling, or treatment for the disposition of produced water, including disposition in road construction maintenance, roadway ice or dust control or other construction, or in the application of treated produced water to land, for activities unrelated to the exploration, drilling, production treatment or refinement of oil or gas." [1]

The New Mexico Environment Department (NMED) was given the responsibility to administer these regulations. To better understand the scientific and technical challenges and opportunities surrounding produced water, NMED and New Mexico State University (NMSU) established the New Mexico Produced Water Research Consortium (NMPWRC or Consortium) through a joint NMED-NMSU Memorandum of Understanding (MOU).

The role of the Consortium is to assist in filling the scientific and technical gaps related to treated produced water reuse. The purpose of this gap analysis and research plan is to provide an overarching multi-year guide to the research priorities**,** efforts, and strategies of the Consortium consistent with the legislation and the NMED-NMSU MOU. The focus of this plan is to address current and near-term research needs, priorities, and gaps. Beyond 2023, after these initial challenges are addressed, additional long-term research needs and opportunities such as innovative treatment technology development, artificial intelligence and machine learning, and infrastructure system optimization modeling could be considered to support the next generation of treated produced water fit-for-purpose reuse.

[1] 2019 HB 546 – Fluid Oil & Gas Waste Act: https://www.nmlegis.gov/Legislation/Legislation?chamber=H&legType=B&legNo=546&year=19

[2] Memorandum of Understanding (MOU) between New Mexico Environment Department (NMED) and New Mexico State University (NMSU) for establishing the New Mexico Produced Water Research Consortium (NMPWRC). https://www.env.nm.gov/new-mexico-produced-water/nmsu-mou/

2. Research Approach

This document, in coordination with other research-related documents such as the annual program plans, QA/QC plan, and sampling guidance, relates the research priorities to be done in the three strategic program areas described in the MOU:

Area 1 - produced water characterization: physical, chemical, microbiological, and environmental toxicity analysis

Area 2 - technology development, deployment, and commercialization; and

Area 3 - economics (including socio-economics), policy, and regulations.

These three strategic areas can be simplified into a few basic research questions:

What is in the produced water?

How can it be cost-effectively treated for various end uses in a safe manner?

What changes are needed in NMED standards, rules, and regulations to meet the requirements of the 2019 Produced Water Act legislation?

Additional questions that can be posed in support of the basic approach include:

Is it feasible for treated produced water to help address future water shortages in New Mexico?

If so, what economic sectors and what locations would benefit the most from an additional water source?

Ultimately, these questions will rely on a thorough science and technology-focused investigation that the Consortium, NMSU, and their partners will be answered through the proposed research.

The Consortium has designed pilot testing and demonstration efforts to support an operational testing and evaluation program. This program will assist New Mexico environmental and natural resources agencies in identifying and evaluating technologies and systems that can support the treatment of produced water for fit-for-purpose reuse. This is part of a new and emerging national strategy and therefore there is limited comprehensive system evaluation data. Large-scale cost and performance information on combined technologies or innovative applications of new technologies are also lacking.

Because the Consortium will depend upon state appropriations, grant funding and donations from Consortium members and sponsors, the available budget for testing and other tasks may vary from year to year for the Consortium. While the Consortium can provide guidance and direction to vendors, contractors, and collaborators, ultimately the efforts and research that will be undertaken will focus on what is proposed under the Consortium Request for Proposal process and other collaborative research and development efforts. The research efforts and approach will be guided by the June 2019 Ground Water Protection Council's (GWPC) *Produced Water Report: Regulations, Current Practices, and Research Needs.* [3] The GWPC analysis was based on two years of work by experts from state regulatory agencies, environmental NGOs, industry experts, and academics. The report is a benchmark publication on the topic of produced water use and reuse. Based in part on Module 3 "Research Needs" of the 2019 GWPC Report, the Consortium, informed by the NMPWRC Technical Steering Committee, will identify New Mexico-relevant

pilot demonstration and/or research projects to address the use of treated produced water outside the oil and gas industry.

In addition, the Consortium will reference, support, and leverage activities carried out pursuant to the U.S. Environmental Protection Agency's (EPA) Water Reuse Action Plan (WRAP) [4] as it pertains to collaborative progress and implementation of water reuse strategies for produced water in New Mexico and other states. The WRAP is part of a national effort to improve the use and reuse of wastewaters by driving progress on reuse and addressing local, regional, and national barriers across a range of technical, institutional, and financial challenges. New Mexico, through the Consortium, leads the WRAP effort for technology development and validation for off-field use of treated produced water. [5] The Consortium continues to work closely with the EPA and the GWPC to establish a National Coordination Council for Produced Water in support of the WRAP.

The Consortium has developed several documents to guide New Mexico's research process. The Goals and Objectives document [6] lists several objectives to meet the intent of the strategic program areas:

- Quantify volumes and characterize the quality of produced water generated in New Mexico, including identification of all constituents found in respective basins and formations and chemical additives used for hydraulic fracturing and directional drilling (Area 1);
- Measure the cost and effectiveness of different treatment approaches that can meet the quality criteria specific to end uses such as road construction, rangeland rehabilitation, agriculture, livestock production, industrial applications, municipal applications, mining, energy, and other uses (Areas 2 and 3);
- Quantify the cost and effectiveness of mineral recovery approaches for produced water, including strategic minerals such as lithium or rare earth elements and other constituents of interest including acids, bases, and salts (Areas 2 and 3);
- Quantify the cost and effectiveness of brine management and disposal (Areas 2 and 3);
- Establish or develop sampling and analysis methods for constituents of concern and sensitivity to appropriate levels of concern in treated produced water (Areas 1, 2 and 3); and
- Assess the health and safety effects of the use of treated produced water including bioaccumulation and toxicity in soils, risks to flora and fauna, effects on surface water quality and associated biota, and groundwater resource (Areas 1 and 3).

[3] Ground Water Protection Council (GWPC). *Produced Water Report: Regulations, Current Practices, and Research Needs. June 2019.* https://www.gwpc.org/sites/gwpc/uploads/documents/Research/Produced_Water_Full_Report___Digital_Use.pdf

[4] U.S. Environmental Protection Agency (USEPA). Water Reuse Action Plan (WRAP). https://www.epa.gov/waterreuse/water-reuse-action-plan.

[5] U.S. Environmental Protection Agency (USEPA). Implement New Mexico Produced Water Research Consortium. https://www.epa.gov/waterreuse/national-water-reuse-action-plan-online-platform?action=4.2

[6] New Mexico Produced Water Research Consortium. Goals and Objectives - 2020. https://nmpwrc.nmsu.edu/wp-content/uploads/sites/83/2020/10/NM-PWRC-Goals-and-Objectives-1.pdf

The Consortium encourages projects designed to fill gaps in analytical methods, explore economics of contaminant removal at various levels, study byproducts generated from produced water treatment, measure contaminants found in treatment byproducts, evaluate viable methods of waste disposal, and research the water quality parameters needed for treated produced water to be suitable for various fit-for-purpose end uses.

Summary Consortium Program Plans and Annual Research Program Summary Reports will be written for each calendar year of the Consortium, identifying future activities and providing important information and guidance on previous work done and what remains to be accomplished. These annual program plan documents will be intentionally brief and are intended primarily for use by regulators and Consortium collaborators to assure that the Consortium addresses stated technical, regulatory, and human and environmental health and safety objectives.

The NMPWRC Operating Plan [7] describes the goals, value proposition, and participants in the Consortium. It also presents the organizational and management structures. The purpose of the research program is described as follows:

> "The Consortium research program will consist of a portfolio of research projects evaluated and approved by the Technical Steering Committee (TSC) with the intent of facilitating treatment technology research and technology development that can:
> - accelerate the implementation and acceptance of policies and regulations for the use of treated produced water in New Mexico;
> - support policies and regulations that protect the environment and human health; and
> - be used as models nationwide."

The overarching research objective is to create a coherent research process that is scientifically robust by using TSC members and NMED personnel as an independent review team and 3rd party laboratories to verify a technology's performance and ability to meet specific identified treatment goals and specifications. This research process will support the NMED as they develop guidance and regulations per the 2019 New Mexico Produced Water Act.

Consistent with this overarching objective, the research will apply existing and emerging technologies to the treatment challenge of complex wastewater in quantifiable ways. The research process is expected to consist predominantly of the application of currently accepted water treatment equipment, materials, and analytical methods. Ideally, the evaluation will be done for different stages of several proposed reuse options, including water collection and infrastructure development, sampling and analysis, water treatment, waste disposal, and socio-economic and ecological risk analysis. The sampling of influent and effluent water quality will be held to the highest standards using the best possible sampling and analytical methods, to build knowledge and trust in the process of treating and reusing produced water and other complex wastewaters.

[7] New Mexico Produced Water Research Consortium. Operating Plan. https://nmpwrc.nmsu.edu/wp-content/uploads/sites/83/2021/06/NMPWRC-Operating-Plan-2021.6.10.2021.pdf

A system-level Process Flow Diagram (PFD) describing the reuse evaluation process is shown in Figure 1. This template will be used to structure and test each proposed treatment system. Treatment systems will be proposed, built, and tested by applicants through a Request for Proposal (RFP) process. Effectiveness of each application will be evaluated by the Consortium, based on scientific and engineering data that is collected from each test. Effectiveness will be judged by the ability of each test to meet the research priorities and objectives related to each test. The Consortium may require pilot projects that propose application of treated produced water outside of a laboratory or greenhouse to be designed to gather the maximum amount of data to support the Consortium's research objectives before proceeding. For example, to ensure a strong return on investment on the research and associated regulatory approvals, a project to evaluate impacts of using treated produced water for rangeland rehabilitation may be required to evaluate several treated produced water sources (e.g., of varying water quality), plant uptake of constituents of concern, impacts to soil, subsurface impacts (e.g., infiltration) and byproduct quality and disposal.

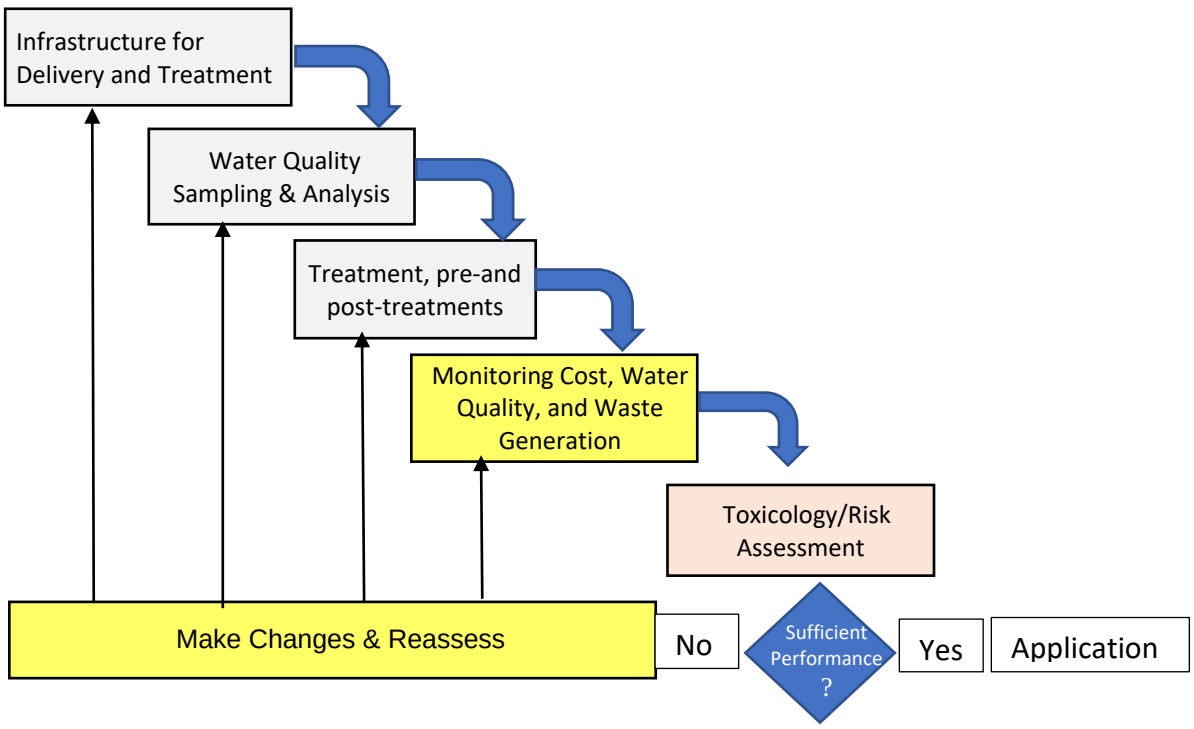

Figure 1. Fit-for-Purpose Reuse Evaluation Process

While the Consortium will support different types of technology research and development, it is important to note that before pilot demonstrations or reuse applications are established, preliminary laboratory and bench-scale research and development data will often be required to show the viability of technologies before moving to larger-scale and more costly pilot projects. The Consortium's selected approach is shown in Figure 2 and is commonly used by federal and

industrial innovative technology research and development agencies such as EPA, the Bureau of Reclamation (BOR), Department of Defense (DOD), and Department of Energy (DOE).

The approach to field testing is as follows. After initial laboratory validation of the treatment process using produced water, the technology is delivered to a treatment site. The influent water is sampled to assess initial quality and pre-treatment needed to address any specific constituents requiring special attention. This provides a baseline quality to determine whether hazardous constituents are removed during treatment and should occur in addition to sampling and analysis that would be previously done in the laboratory to account for variability in produced water sourcing and transportation effects.

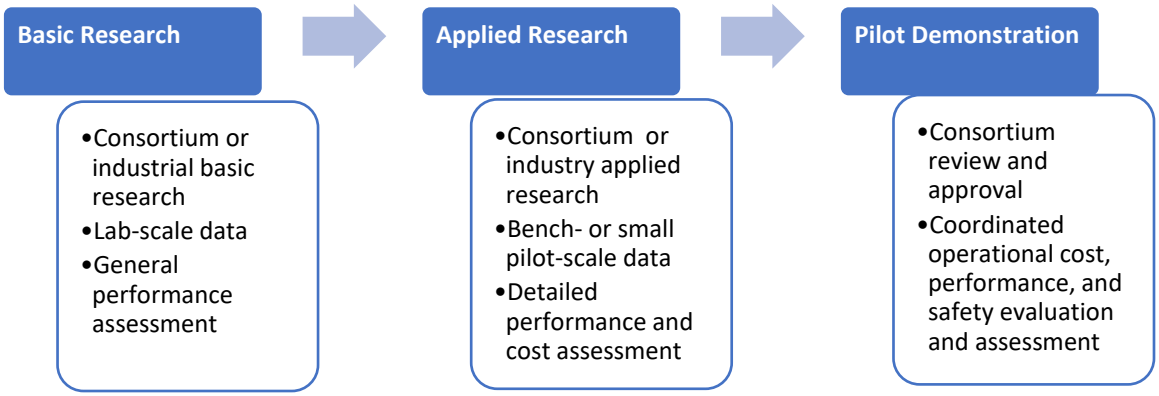

Figure 2. Flow Chart of Research and Pilot Demonstration Efforts

With this baseline information, the proposed treatment method is applied. Pre-evaluation of the method and the preliminary lab results will guide the pre-treatment, treatment, and post-treatment system operation and final treated water quality requirements. Pre-evaluation will also guide the operating approach that can help minimize waste generation and maximize treated water recovery. If possible, real-time or near real-time operational monitoring is encouraged to assess performance and compliance with treatment targets. Post-treatment analysis is required and provides assurance that the treated produced water meets the target water quality criteria. This data can then be used to help evaluate environmental and human risks. Our expectation is that the Consortium will fund and conduct up to six or more projects per year depending upon funding.

In later sections, we discuss more specific process steps and how they will address the identified research gaps within the scope of the Consortium strategic program areas.

Roles of various participants

The Consortium's role is to establish a management framework under which research projects will be conducted that will help to fill the current science, technology, and health and safety gaps associated with fit-for-purpose reuse of treated produced water. This will be accomplished by conducting and supporting basic and advanced research and development of innovation in science

and technology. Further information about the Consortium and its mission can be found at https://nmpwrc.nmsu.edu/about-us/.

The Consortium organizational structure is presented in Figure 3 below. The structure was developed based on successful federal agency approaches to integrate public, private, and academic input on advanced research and development projects. It facilitates collaboration to address and resolve public and environmental issues and concerns associated with the safe treatment and use of produced water.

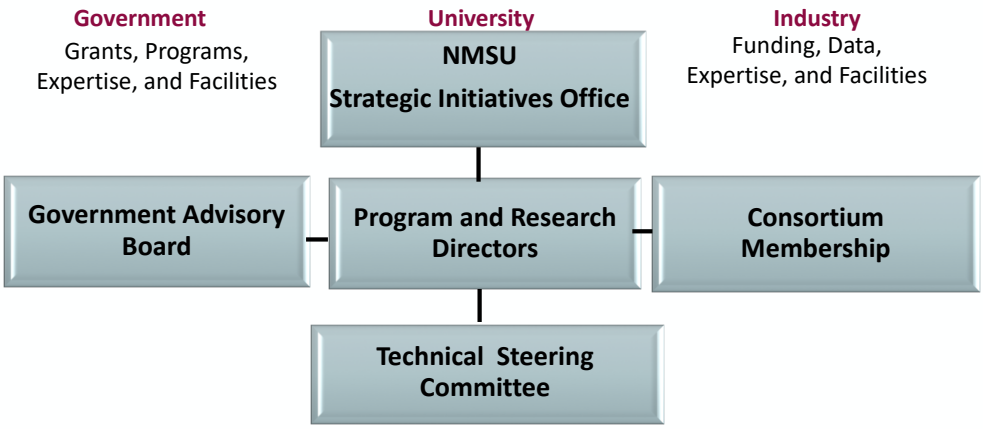

Figure 3. Consortium Collaboration and Organizational Structure

Program and Research Directors. The Program and Research Director Team includes: a Program Director to lead all Consortium efforts; a Research Director to lead and provide technical oversight of all Consortium research efforts; an Operations Manager to handle all Consortium operational issues such as the website, press releases, document tracking, etc.; and Consortium Fellows to coordinate interactions with NMED and facilitate coordination of the delivery of technical and operational information, issues and challenges between NMSU and NMED.

A **Government Advisory Board** (GAB) is composed of state and federal environmental and natural resource management agencies. The GAB provides direction to Consortium management on all operations, planning and research activities. The GAB is led and coordinated by the NMED and their personnel with the support of the Consortium Program and Research Directors Team.

A **Technical Steering Committee** (TSC) is composed of technical representatives of the general Consortium membership to provide technical direction and oversight to the Consortium Research Director. This includes direction on the development of annual research priorities, research and development program plans, research and development project selection and evaluation, and technical input on research and development approaches to fill current and emerging science and technology gaps.

Members of the TSC will also be called upon to provide oversight of all research projects as part of Consortium Project Evaluation Teams. A Team will be assembled, comprised of TSC members and a few NMED personnel, for each research project to provide independent oversight and review by Consortium representatives of associated research plans and activities to minimize conflicts of interest and to support fair and balanced evaluations for the technology vendors. This follows other successful environmental technology evaluation approaches used by DOE, DOD, and the EPA and mimics the EPA's Environmental Technology Verification (ETV) Program. This Committee will be led by the Consortium Research and Program Directors.

The **Consortium Membership** includes representatives from government agencies, academia, water treatment companies, oil and gas production, midstream, and service companies, NGOs, associations, consultants, and technology vendors. Not all members will be involved directly in Consortium research and development efforts but could be interested in produced water treatment or reuse opportunities, or Consortium progress and research information. The Consortium membership coordination, membership recruitment, sponsorship recruitment, and public interaction is managed and coordinated through the NMSU College of Engineering with support from the Program and Research Directors.

The major technical efforts of the Consortium will be conducted through six working groups and their associated Task Committees. Based on recommendations by the Consortium Membership, the Consortium established the following six working groups. They include:

1. An **Infrastructure Working Group** whose role is to help identify current and emerging infrastructure needs to be considered to support and facilitate fit-for-purpose treatment and reuse of produced water.
2. A **Treatment Working Group** whose role is to help identify and coordinate the testing and evaluation of the cost and performance testing of technologies to improve the cost and performance and the overall quality of treated produced water to better support fit-for-purpose reuse.
3. An **Applications Working Group** whose role is to help identify potential applications compatible with treated produced water and to help identify the required treatment levels of produced water for various applications.
4. A **Water Quality Working Group** whose role is to evaluate and quantify the spatial variation in produced water quality across the state and to identify analytical approaches to measure produced water constituents.
5. A **Water Quantity Working Group** whose role is to evaluate and quantify the spatial and temporal variation in produced water quantity across the state from producers; and
6. A **Risk and Toxicology Working Group** whose role is to identify appropriate environmental and human risk and toxicology testing approaches to assess the potential human and ecological risks from the use of treated produced water.

These six working groups and their associated Task Committees are designed to work in an integrated fashion to address both the technical risks (Infrastructure, Treatment, and Water Quantity and Quality Working Groups) and environmental and ecological risks (Treatment, Risk and Toxicology, and Water Quality Working Groups) for various fit-for-purpose applications

(Applications). Working Groups and their associated Task Committees include interested member representatives from the Technical Steering Committee. These technical representatives are encouraged to be involved in multiple Working Groups and associated Task Committees to make sure that there is coordination and synergy of efforts across all the Working Groups and their associated Task Committees.

3. Ranking Research Priorities (Gap Analysis)

The Consortium undertook a review of multiple reports and publications from January to November 2020 in order to identify research needs and gaps surrounding produced water treatment relevant to New Mexico. Appendix A provides details on the sources of information used for this review. Table 1 summarizes these topics and the supported Strategic Program Area(s).

Table 1. Ranking of Produced Water Research Priorities

Priority Task	Strategic Program Area(s)
1) Establish bench- and pilot-scale research, development, and demonstration testing to support effective and economical pre-treatment and treatment trains. These should include: a) improvements in enhanced evaporation and desalination technologies; b) improve or optimize pre-treatment and post-treatment technologies to address specific water quality challenges related to scale buildup or specific constituents; c) analyze the complex characteristics of a specific produced water; d) manage variability in untreated and treated produced water; e) significantly reduce high total dissolved solid levels, organic constituents, metals, and naturally occurring radioactive material (NORM) to reduce risks; f) handle residual materials and wastes appropriately; and g) develop methods for separation of saleable products during treatment.	Area 1- produced water characterization; physical, chemical, microbiological, and environmental toxicity analysis Area 2- technology development, deployment, and commercialization
2) Evaluate the costs, benefits, and risks in achieving the identified treatment standards	Area 3 - economics, policy, and regulations
3) Use collected data and data analysis to inform risk-based decisions to support the development of reuse programs that are protective of human health and the environment	Area 1- produced water characterization; physical, chemical, microbiological, and environmental toxicity analysis Area 3- economics, policy, and regulations.

4) Encourage treated produced water reuse to eliminate fresh water use in the oil and gas sector and create additional water supplies for uses outside the oil and gas sector	Area 3- economics, policy, and regulations.
5) Improve understanding of the composition of specific produced water sources and identification of the health and environmental risks of reuse or release	Area 1- produced water characterization; physical, chemical, microbiological, and environmental toxicity analysis
6) Provide through an easy-to-use data portal and GIS system the location and temporal variation in produced water volume and quality potentially available for applications	Area 3- economics, policy, and regulations.
7) Use produced water quality data to determine the standards of treatment that must be met to make the produced water fit-for-purpose reuse	Area 1- produced water characterization; physical, chemical, microbiological, and environmental toxicity analysis
8) Optimize leak detection systems to minimize spills and spill volumes to reduce environmental and ecological risks of produced water use	*Additional Goal*
9) Develop or improve upon existing analytical methods for the characterization of produced water constituents as needed and establish methods for assessing toxicity impacts of produced water	Area 1- produced water characterization; physical, chemical, microbiological, and environmental toxicity analysis
10) Establish a government regulatory working group as identified in the GWPC Produced Water Report to facilitate infrastructure development including the use of excise taxes to fund project development	Area 3- economics, policy, and regulations.
Identified New Mexico-Specific Research Priorities	
Develop an infrastructure Master Plan	*Additional Goal*
Establish an educational outreach program to engage stakeholders in the state-of-the-science of produced water treatment and reuse	*Additional Goal*
Development of automated treatment systems that can be operated remotely with little or no human intervention	*Additional Goal*
Evaluate impacts on greenhouse gasses from produced water treatment and reuse	*Additional Goal*
Consider non-traditional water supplies, such as produced water reuse, in future regional and state water planning	Area 3-economics, policy, and regulations.

While Consortium research will address many of the identified research priorities at least nominally, this list of priorities can serve as a guide for future research and partnership opportunities. These priorities are further addressed in Section 4, Consortium Tasks and Milestones, below.

4. Consortium Tasks and Milestones

This section describes the types of projects that are planned and are likely to be carried out by the Consortium or in conjunction with contractors and others in Calendar Years (CY) 2020-2024.

Projects could include bench and field studies, greenhouse or other controlled tests, industrial applications, or other applications designed and implemented in accordance with all existing applicable local, state, and federal guidelines or regulations.

4.1 Strategic Program Area (1)-Produced water characterization: physical, chemical, microbiological, and environmental toxicity analysis.

4.1.1 Produced Water Quality Sampling and Analysis Projects

In 2020, the Water Quality working group began to collect data on produced water quality. This survey included several tasks, as listed below:

Request for Information on Analytical Capabilities. The Consortium prepared a request for information from commercial analytical laboratories to collect information on the analytical costs, efficacy, and throughput of current analytical methods for high salinity produced water for over 300 constituents of interest. This information will be used to identify analytical methods and costs for establishing future analytical, toxicology, or method development needed to support future health and safety regulations and policies.

In addition, NMSU scientists and Consortium members have published a critical review of produced water analytical methods in use at the time of this document production. [8] The review is also a source of information on the constituents of interest in produced water, and the pertinent regulatory frameworks that can guide analytical method development. The review will be used as a foundational document for future analyses of constituents of concern during treatment testing.

Development of a Tiered Sampling and Analysis Approach. The Water Quality working group identified a tiered sampling approach for use during pre-treatment, treatment, and post-treatment. The produced water analyses are divided into four tiers based on the needs of different analyses, including cost, complexity, and turn-around time as noted in Figure 4.

[8] Jiang, W., Lin, L., Xu. X., Cheng, X., Zhang, Y., Hall, R., Xu, P. (2021). A Critical Review of Analytical Methods for Comprehensive Characterization of Produced Water. Water, 2021, 13(2), 183; https://doi.org/10.3390/w13020183.

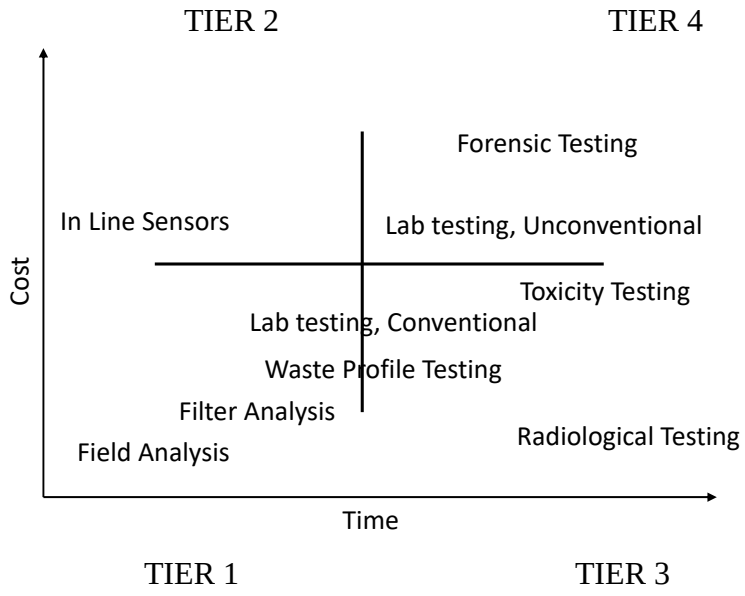

Figure 4. The cost and turnaround time of produced water analyses

As presented in Table 2, Tiers 1 and 2 analysis involves the use of in-line sensors, field parameters, and onsite testing for real-time, continuous monitoring, and routine process control. Real-time sensors and field-based analytical techniques are encouraged for use where appropriate to reduce analysis costs and speed analysis times (real-time or near-real-time) without sacrificing data quality.

Tiers 3 through 4 focus on detailed characterization and Tiers 1 and 2 data verification needed to support state and federal discharge permit compliance and evaluation of treatment technology processes for fit-for purpose uses. Conventional and unconventional lab testing, Whole Effluent Toxicity (WET) testing, and leachate testing will be conducted using advanced analytical tools.

In addition to target analysis, Tier 4 includes non-target analysis using high resolution mass spectroscopy (HRMS) approaches. This is the most time-consuming and most costly analysis approach, but can be used to discover and/or fingerprint any potential "unknown" chemicals in raw and treated produced water.

This tiered approach assures that the appropriate physicochemical, biological, and toxicity analyses are performed when and where needed to support public and environmental health and safety and support regulatory and policy development and compliance.

Table 2. Multi-tiered approach for produced water characterization

Level	Use	Description	Parameters	Frequency
Tier 1	Continuous monitoring, bulk testing, KPI rapid analysis, process control	In-Line Sensors Field Parameters Filter Analysis	Flow, TSS, TDS, TOC, pH, ORP, iron, H_2S, TPH, level sensing, carbonate	Realtime, continuous, and routine
Tier 2	Detailed characterization, routine monitoring, and Tier 1 data verification	Conventional Lab Testing	Wet chemistry, ICP-OES, ICP-MS, GC, GC-MS, HPLC	Baseline, quarterly, when experiencing data excursions in Tier1. Proving up treatment efficacy and reliability, beneficial reuse investigation
Tier 3	Discharge permit compliance, modeling treatment technology; Waste disposal profile generation; Risk assessment and data capture for fate/transport modeling.	Unconventional Lab Testing; WET Testing	LC-MS, Gamma Spec, High Res GC-MS; Acute and chronic toxicity	When evaluating technology and management processes. As per permit/regulatory agency
		Leachate Testing	TCLP, SPLP, LEAF testing of residual waste	
		Bio-mobility and accumulation testing	Tier 1,2,4 analysis of treated effluent on soil, plant, tissue samples	
Tier 4	Source apportionment, fingerprinting, identification of unknown constituents	SEM/EDX, XRD, FEEM, HRMS, biomarker analysis, isotopic analysis		Evaluating technology and management process. Basic research of method development. Event response. Beneficial reuse investigations. Unknown constituent identification.

Note: TSS: total suspended solids; TDS: total dissolved solids; TOC: total organic carbon; ORP: oxidation reduction potential; TPH: total petroleum hydrocarbon; ICP-OES: inductively coupled plasma-optical emission spectroscopy; ICP-MS: inductively coupled plasma-mass spectroscopy; GC-MS: gas chromatography-mass spectroscopy; HPLC: high-performance liquid chromatography; LC-MS: liquid chromatography–mass spectroscopy; TCLP: toxicity characteristic leaching procedure; SPLP: synthetic precipitation leaching procedure; LEAF: Leaching Environmental Assessment Framework; SEM/EDX: scanning electron microscopy/energy dispersive X-ray spectroscopy; XRD: X-ray diffraction; FEEM: Fluorescence excitation-emission matrix; HRMS: High resolution mass spectrometry.

Development of a Guidance Document on Produced Water Sampling. A guidance document on produced water sampling and analysis has been developed by the Consortium to assure that samples are collected, stored, and shipped correctly. [9] This provides a consistent set of produced water sampling and analysis procedures that will be used by all laboratory and field personnel. The objective is to assure that all data is collected appropriately and will include blanks, duplicates, and spiked samples to verify analysis integrity.

[9] New Mexico Produced Water Research Consortium. Guidance on Produced Water Sampling Procedure. https://nmpwrc.nmsu.edu/wp-content/uploads/sites/83/2021/06/PW-Samping-Protocol-draft-final-2020_5_11.6.10.2021.pdf.

Detailed Produced Water Analysis. NMSU has unique state-of-the-art analytical techniques available to measure constituents at very low concentrations, and identify specific compounds at an accuracy of 0.0001 of molecular weight. These methods will be tested and validated for analysis of potentially toxic constituents or potentially unknown constituents at ultra-trace levels. If validated, these methods will be useful to assure that all constituents of interest have been measured.

NMSU will support the Consortium for analysis of produced water samples. The focus will be on detailed water quality mapping as well as identification of constituents of potential concern or risk in reuse. The results are expected to be used by regulatory agencies in defining water quality requirements for specific fit-for-purpose applications.

Analytical Method Development. Analytical and forensic research chemists will be identified by the Consortium at national laboratories, research universities, public health agencies, and private laboratories to identify needed expertise. Collaborations with these experts will be formed to tap their experience in developing analytical methods, when necessary, to reduce the occurrence of false negative results in high-salinity environments.

Note on Data Quality: High-quality analyses and final results are an important part of the Consortium programs. See the Quality Assurance plan and implementation guidance available from the following references.
SW-846: https://www.epa.gov/hw-sw846/sw-846-compendium
NMPWRC Scientific Integrity statement https://nmpwrc.nmsu.edu/scientific-integrity/
NMPWRC Guidance on Treated and Untreated Produced Water Sampling Procedure https://nmpwrc.nmsu.edu/wp-content/uploads/sites/83/2021/06/PW-Samping-Protocol-draft-final-2020_5_11.6.10.2021.pdf

4.1.2 Development of a Web-based Produced Water Quality Data Portal

Based on discussions with New Mexico water-quality database users, the Consortium will work with the NM Bureau of Geology, the Petroleum Resource Recovery Center, the GWPC, and produced water quality and quantity data generators and users to upgrade existing New Mexico produced water databases such as NMOCD Statistics [10] and Go-Tech [11] to meet the goals of the 2019 NM Water Data Act. This effort will create a web-based data portal in cooperation with these groups to enable the public and industry to easily query and evaluate produced water quality and quantity data at the township geographic level. The purpose will be to evaluate produced water treatment needs for various fit-for-purpose applications. The database will also include available metadata to assist data users in evaluating data quality and sources.

[10] New Mexico Oil Conservation Divisions. OCD Statistics. https://www.emnrd.nm.gov/ocd/ocd-data/statistics/
[11] Go-Tech. http://octane.nmt.edu/gotech/

The produced water data portal will be designed to create a hierarchy of accessible data tiers. These tiers assure that, when appropriate, data will be anonymized to protect proprietary information from being released but will allow all produced water constituent data to be made available to the public for review. The aim is to eliminate concerns about the release of proprietary information on chemical additives while presenting an open data source. The Consortium has established a non-disclosure agreement and a need-to-know authorization policy and procedure to protect confidential business information, while providing transparency to the public. This approach assures that all produced water quality data can be submitted and used by NMSU and the Consortium.

Water Sampling and Analysis Research and Development Schedule. Table 3 provides a recommended timeline for the Consortium to accomplish expected tasks for this strategic program area. The schedule proposed depends on sufficient Consortium funding to support the Testing and Evaluation Program.

Table 3. Sampling and Analysis Research and Development Schedule

Task	Objective	Start	Finish
Produced water sampling and analysis methods evaluated	NM produced water sampling and analysis protocol	2020	2021
Consistent water treatment performance monitoring and sampling methods	Standard Tiered monitoring and analysis guidance	2020	2021
Cost-effective water quality analysis	RFI on Analytical Cost and Efficacy	2020	2021
Updated produced water quality and quantity data portal	Web-based NM produced water data portal	Mid- 2021	2022
Policy and procedures for protection of proprietary data but full disclosure of chemicals	Integration of need-to-know in data portal and approved NDA Procedure	Mid-2021	2021
Produced Water Data Collection Initiative	Collect, analyze, and update produced water quality data	2021-2024	2021-2024
Identify the risks and toxicology of constituents in produced water	Quantify the toxicity and constituents of concern during reuse and discharge	2021	Updated annually
Analytical Method development for constituents of concern	Method development team approach	2022-2023	2023-2024

4.2 Strategic Program Area (2)-Technology development, deployment, and commercialization

4.2.1 Pre, Post, and Treatment System Research and Development Projects

Treatment system development (including pre and post treatment) is one of the highest priority tasks to be undertaken by the Consortium. The Consortium has created a guidance document for treatment research and pilot testing that is expected to be the primary guide for the treatment development and project deployment. [12] Further, an RFP document has been created to guide those proposing projects to be funded by the Consortium and its collaborators. [13] The development process for high-performing pre-, post-, and treatment systems includes several tasks, as listed below.

Note that in 2021, and later as required by NMED, the Consortium will not support or participate in any research activities that involve the environmental discharge of untreated produced water or treated produced water outside the oilfield without NMED permit authorization.

Bench-Scale Technology Testing. Bench-scale or small-pilot scale test data collection will be strongly encouraged before larger pilot demonstration applications of a technology are considered. Bench-scale testing and data collection should be focused on the appropriate cost and performance data needs to support pilot- or field-scale applications.

Laboratory or bench-scale testing is expected to be conducted at Consortium-participating sites and facilities such as university, federal, state, or industry locations to enable high-quality validation of operations and performance. The Consortium will also coordinate or host research funding opportunities for Consortium members and technology providers to facilitate basic science advances and innovation.

Pilot-scale Technology Testing. Pilot demonstrations larger than bench-scale are often needed to quantify real-world operating performance and costs of new treatment technologies. Pilot demonstrations are complex and often expensive efforts, especially with the level of monitoring and testing needed to provide high-quality cost and performance data. It is also essential that public and environmental health and safety requirements are met. Therefore, each proposed project will be reviewed by a Consortium Project Evaluation Team to consider the proposed schedule and operational benefits of different technologies and applications, timing issues, and "shovel readiness."

In an operational scenario, cost-effective and safe treatment usually requires a system of pre-treatment, treatment, post-treatment, and waste disposal technologies and processes to meet the system design standards or resource recovery requirements. This is highlighted in Figure 5 below, which shows a generalized treatment process for any fit-for-purpose use of produced water:

[12] New Mexico Produced Water Research Consortium. Guidance on Produced Water Treatment Research, Development, and Pilot-Scale Demonstration Testing and Evaluation. https://nmpwrc.nmsu.edu/wp-content/uploads/sites/83/2021/06/Pilot-Testing-Guide_November2020_6.10.2021.pdf

[13] New Mexico Produced Water Research Consortium. Request for Proposal. https://nmpwrc.nmsu.edu/requests-for-proposals/

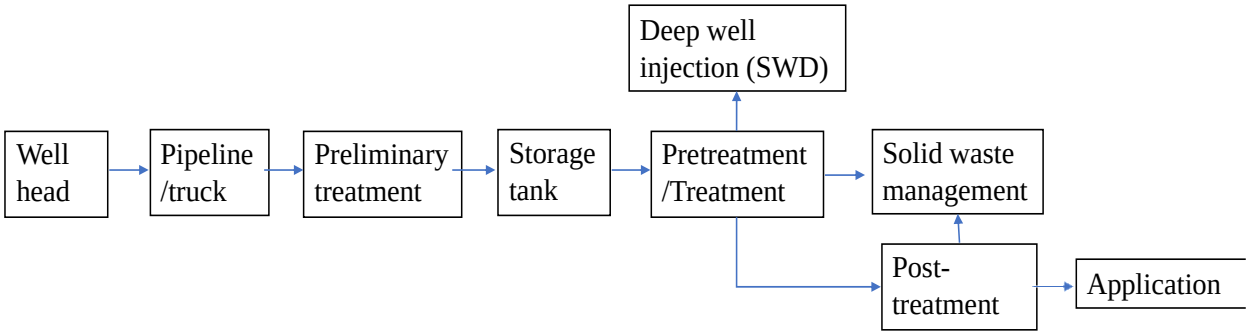

Figure 5. Example produced water treatment train

While research and development testing in the laboratory of each element of the treatment process is important, pilot-scale demonstrations or a full-scale system are needed to get the correct operational performance of the integrated processes and the associated cost, operability, maintainability, and health and safety impact. Full-scale demonstration projects will be strongly encouraged and supported by the Consortium to fill this information gap.

4.2.2 Treatment Program Plan

The Consortium has identified and established a complete research and development program plan and the requirements needed to address industry and public concerns of the cost, performance, and public health and safety aspects of fit-for-purpose reuse of produced water. Research and development improvements will be encouraged for:

- pre-treatment,
- treatment and optimized water recovery,
- post-treatment of treated produced water for fit-for-purpose applications,
- waste management including waste minimization and mineral/resource recovery,
- waste disposal, and
- environmental health and safety monitoring.

Consortium research will focus on the environmental and human health impacts associated with the reuse of treated produced water for various fit-for-purpose end uses, including but not limited to:

- Carbon sequestration and rangeland rehabilitation;
- Site remediation;
- Energy production and storage, including hydrogen;
- Mineral or resource recovery:
- Road construction and maintenance; and
- Industrial processes, such as manufacturing and solution mining.

As RFPs are released for each year of the Consortium, the degree to which these R&D projects meet the program areas and objectives will be considered. Projects will be selected preferentially to fill gaps in knowledge for various uses or applications.

A complete test and operational plan, including a sampling plan, a health and safety plan, and a QA/QC plan is required from vendors before pilot-testing will be undertaken as identified in the Consortium's "Guidance on Produced Water Treatment Research, Development, and Pilot-Scale Demonstration Testing and Evaluation". [12]

Regulatory Oversight for Pilot-testing Sites. The regulatory oversight of indoor laboratory and bench-scale testing of treatment technologies is well constrained and understood. However, field-level pilot-scale testing, especially using produced water, is a bigger concern. There are multiple agencies that may have jurisdiction over operations at a pilot-test site. This includes disparate agencies such as NMED, the State Land Office, the Bureau of Land Management (BLM), and New Mexico Energy Minerals and Natural Resources Department (EMNRD) OCD. Some existing test facilities operate under groundwater discharge permits issued and enforced by NMED. In addition, there are relevant state and federal regulatory considerations related to radiation control, air emissions, and solid and hazardous waste management. All Consortium project participants will comply with any and all applicable federal, state and local regulations and guidelines.

Treatment and Pretreatment Technology Screening Approach. Figure 6 below provides a general overview of the types of technologies that may be evaluated to address pre-treatment, treatment, post-treatment, waste management and application challenges in meeting effluent water quality requirements for potential use cases.

The Consortium has developed a screening approach for produced water treatment technologies to fill knowledge gaps for fit-for-purpose applications. Because it is unknown what technologies will be proposed and tested by Consortium partners and RFP respondents, screening will begin with a broad approach, incorporating technologies that are known to be used for produced water treatment. As the efficacy of various technologies evolve, the Consortium will use screening to identify which technologies are best fitted to different fit-for-purpose treatment methods. Additional research is needed before the Consortium can establish comprehensive treatment technology screening criteria for the full suite of produced water constituents that are relevant to different fit-for-purpose reuse applications and appropriate for establishing environmental and human health regulatory protections.

Research and operational history have shown that pretreatment is a very important consideration for both conventional and unconventional produced water, and that for membrane systems treating produced water, effective pretreatment is likely a big challenge. Therefore, one of the most important performance and operational targets of the Consortium is to test various pretreatment methods, preferably as a part of total treatment systems. For this reason, the Consortium is using the standards set by the Produced Water Society (PWS) for produced water pre-treatment for pH, oxidation reduction potential, turbidity, and organic/hydrocarbon content (PWS, 2020). [14]

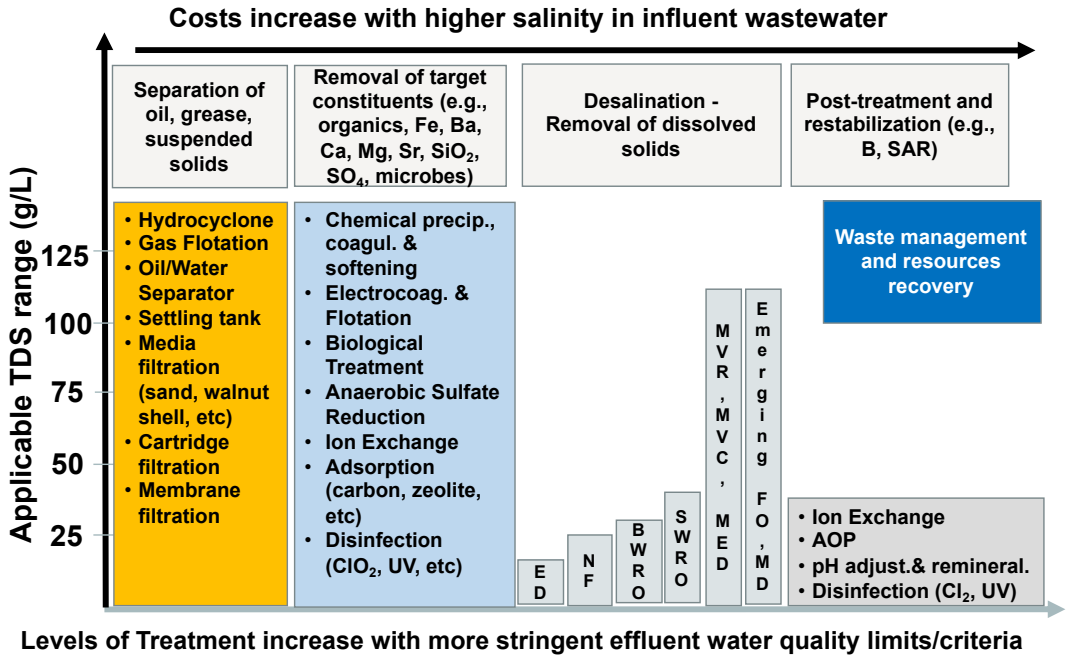

Figure 6. Overview of produced water treatment technologies for fit-for-purpose reuse

Note: ED-electrodialysis, NF-nanofiltration, BWRO-brackish water reverse osmosis, SWRO-seawater reverse osmosis, MED-multi-effect distillation, MVC-mechanical vapor compression, MVR-mechanical vapor recompression, FO-forward osmosis, MD-membrane distillation, AOP - advanced oxidation processes, UV-ultraviolet light, SAR-sodium adsorption ratio

As the salinity of treated water increases, the number of applicable treatment technologies is reduced. Most standard membrane technologies perform poorly for salinities above 60,000 ppm TDS, though some newer high-pressure membranes have been shown to be effective at up to 100,000 ppm TDS. For salinities above that value, thermal technologies are needed. Currently thermal technologies can treat very high TDS produced waters in the $1.00-$2.00 per barrel range. This suggests that treatment technology operating costs for reuse of produced water are approaching the 'tipping point" where treatment and reuse of even high salinity produced water are competitive with current produced water disposal practices and costs in many basins today. To address system-level produced water treatment, the Consortium in the future could encourage the evaluation of combined pre-treatment, treatment, and post-treatment systems or treatment trains for fit-for-purpose applications through the RFP process.

[14] Produced Water Society. A Common Clean Brine Specification for Reusing Recycled Produced Water – Draft Guidelines. A publication by the Produced Water Society – released for consultation 26th June 2020. https://www.owrb.ok.gov/2060/PWWG/PW_CommonWaterQualityGuideline.pdf

The DOE created in 2021 a new desalination roadmap that includes produced water treatment. [15] The Consortium will continue to participate in reviewing research proposed in the roadmap to identify appropriate innovative treatment technologies for consideration and evaluation. If laboratory-scale research and bench-scale studies do not provide assurance that a viable path to meet reasonable cost and performance targets is likely for a technology, that technology will be dropped from consideration, and the Consortium will focus on more viable technical options for evaluation.

Treatment Cost and Performance Research Schedule. Table 4 presents the schedule for technical and regulatory research and development efforts. To move forward with projects focused on pre-treatment, treatment, and post-treatment projects, the TSC and NMED will review basic and pilot research approaches and project opportunities. The schedule proposed depends on sufficient Consortium funding to support the Testing and Evaluation Program.

Table 4. Treatment Technology Research and Development Schedule

Task	Objective	Start	Finish
Finalize bench-scale and pilot-scale testing guidance and screening criteria	Establish pilot-testing approach	2020	2021
2021 Call for projects for pre-treatment, treatment, and waste management for fixed and mobile systems	Selection of 5-10 projects based on funding needs, funding availability, and technical innovation	2021	2022
Summarize Results and lessons learned	Summary of cost, performance, and health and safety benefits	2021	Mid-2022
2022 Call for projects for pre-treatment, treatment, and waste management for fixed and mobile systems	Selection of up to 5-10 projects based on funding needs, funding availability, and technical innovation and application	2022	2023
Summarize Results and lessons learned	Summary of cost, performance, and health and safety benefits	2022	Mid-2023
2023 Call for projects for pre-treatment, treatment, and waste management for fixed and mobile systems	Selection of up to 5-10 projects based on funding needs, funding availability, and technical innovation and application	2023	2024
Summarize Results and lessons learned	Summary of cost, performance, and health and safety benefits	2023	Mid-2024
2024 Call for projects for pre-treatment, treatment, and waste management for fixed and mobile systems	Selection of up to 5-10 projects based on funding needs, funding availability, and technical innovation and application	2024	2025
Summarize Results and lessons learned	Summary of cost, performance, and health and safety benefits	2024	Mid- 2025

4.2.3 Technology Cost and Performance Monitoring and Evaluation

The efforts identified in this section focus on ways to reduce barriers to the acceptance and use of the evaluated treatment technologies and approaches, by assuring that the results of testing are thoroughly documented, evaluated against industry standards, and include accurate and trustworthy data. Involvement of government agencies, industry, academia, the environmental

community, and regulatory agencies in the assessment, evaluation, and verification of innovative technology cost and performance is essential.

The Consortium treatment technology cost and performance evaluation approach is based on a series of national environmental technology remediation and verification programs established in the late 1990s and early 2000s. These programs were designed to move innovative treatment technologies into routine use and accelerate full-scale applications of emerging new technologies. Our approach is based on four major national environmental pilot-scale technology evaluation programs including:

- EPA's Superfund Innovative Technology Evaluation (SITE) Program - established to work with state and federal regulatory agencies and technology providers to identify the cost and performance of innovative soil and water treatment and remediation technologies (EPA, 2003). [16]
- The Federal Remediation Technology Roundtable (FRTR) a Consortium established in 1995 to coordinate federal agency use and collection of data to establish standardized technology cost and performance comparisons. "Guide to Documenting and Managing Cost and Performance Information for Remediation Projects," (EPA, 1998). [17]
- DOE's Innovative Treatment Remediation Demonstration (ITRD) Program - established in 1994 to work with state and federal regulators, DOE and EPA laboratories, the EPA Site Program, to utilize the FRTR approach to reduce regulatory and operational risks of innovative treatment technologies at DOE sites. [18]
- EPA's Environmental Technology Verification (ETV) Program - established to utilize independent third parties, such as national laboratories and technical associations, to conduct full-scale, field operations and evaluate and verify the operational cost and performance of environmental monitoring, site characterization, and hazardous waste treatment technologies (EPA, 1996). [19]

Borrowing from these successful technology testing and evaluation programs, the Consortium has established a technology cost and performance verification process for pilot demonstrations projects. This process is described in the Consortium bench and pilot-scale testing and evaluation guidance document. [12]

[15] Tzahi Cath; Shankar Chellam; Lynn Katz; Richard Breckenridge; Carolyn Cooper; Kirk Ellison; Jordan Macknick; Cameron McKay; Kaleisha Miller; Jason Monnell; Nalini Rao; James Rosenblum; David Sedlak; Jennifer Stokes-Draut. 2021. National Alliance for Water Innovation (NAWI) Technology Roadmap: Resource Extraction Sector. DOE/ GO-102021-5567. https://www.nrel.gov/docs/fy21osti/79895.pdf

[16] EPA, 2003. U.S. Environmental Protection Agency. Superfund Innovative Technology Evaluation Program (SITE) Technology Profiles, Demonstration Program - 11th Edition Volume 1.

[17] EPA, 1998. U.S. Environmental Protection Agency. Federal Remediation Technology Roundtable, "Guide to Documenting and Managing Cost and Performance Information for Remediation Projects", EPA 542-B-98-007.

[18] Hightower, M. 1995. DOE`s Innovative Treatment Remediation Demonstration Program accelerating the implementation of innovative technologies. https://www.osti.gov/servlets/purl/104489

[19] EPA, 1996. U.S. Environmental Protection Agency. A Guidance Manual for the Preparation of Site Characterization and Monitoring Technology Demonstration Plans, Consortium for Site Characterization Technology.

As shown in Figure 7, the project review includes three phases:

- Project planning;
- Development, review, and approval of a demonstration plan highlighting operations and testing, data collection and monitoring, performance assessment; and
- Project and process cost and performance evaluation (provided by the testing group), and an independent technology verification analysis provided by Consortium members (Project Evaluation Team) including a final performance verification report.

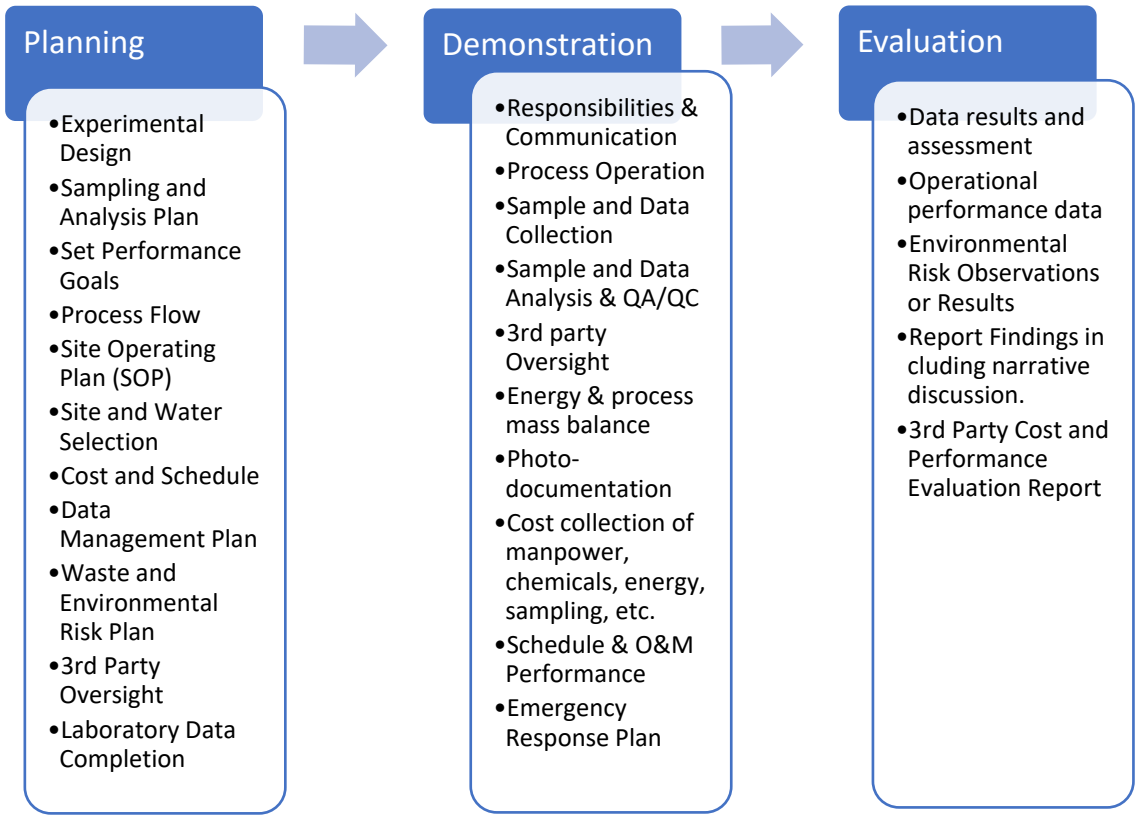

Figure 7. Flow Chart of pilot demonstration monitoring and analysis tasks

The planning and testing steps in Figure 7 assure that the test plan incorporates all the elements needed to provide data of appropriate quality sufficient to reach a defensible position by the NMED regarding cost, performance and public health and safety of the treatment system for the application tested. This process assures that the information collected delivers enough information to provide a safe and economical path for use of the technology or process. The Consortium will not fund or review any pilot-scale technologies or systems that do not meet the project review and reporting requirements identified in Figure 7.

[12] New Mexico Produced Water Research Consortium. Guidance on Produced Water Treatment Research, Development, and Pilot-Scale Demonstration Testing and Evaluation. https://nmpwrc.nmsu.edu/wp-content/uploads/sites/83/2021/06/Pilot-Testing-Guide_November2020_6.10.2021.pdf

By design, all the information needed from the vendor for the Consortium Project Evaluation Team to prepare an independent project evaluation report or "Demonstration Cost and Performance Evaluation Report" will be made available to assure a fair and complete assessment. This approach is required to provide an unbiased technical, health and safety, and regulatory assessment of system operation and maintenance costs, performance, and health and safety aspects.

Based on this evaluation and review, the Consortium Project Evaluation Team can provide a letter of verification of performance to the vendor. This approach has been used successfully in the EPA Environmental Technology Verification Program to enable vendors to use the evaluation report and verification letter as supporting information to use the technology at other sites.

The reports will be technical reports of 20-30 pages, patterned after the format suggested by the Federal Remediation Technology Roundtable. [20] These reports will provide industry, regulatory, commercial user groups, and the public with high-level, summary information needed to understand the benefits, liabilities, and opportunities of the evaluated technology.

Treatment Technology Cost and Performance Evaluation Tasks. Table 5 provides a recommended timeline for the Consortium (and collaborating vendors) to accomplish the expected tasks for this strategic program area. The schedule proposed depends on sufficient Consortium funding to support the Testing and Evaluation Program.

Several technology companies have expressed interest in doing research that is self-funded that is complementary to Consortium goals and efforts. Additionally, it is possible that some technologies developed through federal agency research programs will be directed to the Consortium for an independent operational testing evaluation. In support of those projects, the Consortium will establish a Project Evaluation Team for pilot-scale demonstration projects to provide a similar independent review of cost, performance, and health and safety aspects of the technology and prepare a verification report. As noted above, if appropriate, the Consortium can provide the vendor with a certification of performance.

The Consortium goal is to support and evaluate as many as eight or 10 technologies each year.

[20] Federal Remediation Technologies Roundtable. https://frtr.gov/

Table 5. Treatment Technology Cost and Performance Evaluation Tasks and Schedule

Task	Objective	Start	Finish
2021 Establish Consortium Project Evaluation Teams	Establish 3-6 bench and pilot scale review teams based on project expertise needed	2021	2021
Prepare Cost and Performance Reports	Summary reports of cost, performance, and health and safety benefits for each project	2021	2022
2022 Establish Consortium Project Evaluation Teams	Establish 3-6 bench and pilot scale review teams based on project expertise needed	2022	2022
Prepare Cost and Performance Reports	Summary reports of cost, performance, and health and safety benefits for each project	2022	2023
2023 Establish Consortium Project Evaluation Teams	Establish 3-6 bench and pilot scale review teams based on project expertise needed	2023	2023
Prepare Cost and Performance Reports	Summary reports of cost, performance, and health and safety benefits for each project	2023	2024
2024 Establish Consortium Project Evaluation Teams	Establish 3-6 bench and pilot scale review teams based on project expertise needed	2024	2024
Prepare Cost and Performance Reports	Summary report of cost, performance, and health and safety benefits for each project	2024	2025

4.2.4 Public and Environmental Health, Safety, and Risk Analyses

This section outlines the tasks to be performed related to health and safety risks of the use of treated produced water. The section also addresses the efforts to be undertaken to address and educate the public about human, environmental, and ecological safety and risk, and risk evaluation. This includes both the Consortium's encouragement of toxicology testing and analysis, and educational outreach related to produced water quality, treatment, and the potential for safe use. This work will draw heavily on the analytical and treatment tasks mentioned in sections 4.1.1 and 4.2.1 and relates closely to Strategic Program Areas (1) and (3).

Chemical analysis of produced water has shown that produced water contains a wide range of mineral constituents and chemicals, mostly naturally occurring from millions of years of contact with geologic strata and organic matter, but also from chemicals introduced during drilling, hydraulic fracturing, and oil production operations (GWPC, 2019). [3] Produced water is therefore a water source that must be treated for most applications, especially those outside the oil and gas sector. The effectiveness of the treatment process used to remove these constituents will determine the applicability of the water for a specific use and will dictate the human and environmental toxicology and risk profile related to that specific produced water source, volume, and use.

Any constituents remaining in produced water after treatment may have characteristics that require prolonged observation to assess subsequent long-term toxicology to human or environmental health and safety. While the Consortium intends to strongly support this kind of assessment, the time frames available to the Consortium efforts may not lend themselves to full-scale quantitative risk assessments for every constituent of interest. That said, the Consortium will collaborate with NMED, New Mexico Department of Health (NMDOH), EPA, and NMSU among others to contribute high-quality and substantive data to risk assessment efforts related to treated produced water use.

Risk Evaluation Process. The Consortium will develop a risk evaluation process guided by the needs expressed in the GWPC report, Module 3: [3]

> "Any expansion of produced water reuse or discharge outside oil and gas operations will come with a host of questions from a variety of stakeholders. These stakeholders and decision-makers range from regulators and operators to environmental groups as well as the potential end-users of treated produced water. A common question will be, "What are the benefits and risks?"
>
> There has been rapid growth in both research and technology development aimed at characterizing and treating produced water – initially for the purpose of reuse within oil and gas operations. As attention turns toward more in-depth assessment of the potential for other alternatives, the scope of considerations expands significantly to include new, complex issues ranging from liability to potential ecological and health hazards."

The GWPC report suggests a risk assessment/risk management framework endorsed by the National Research Council (NRC) as the recommended Produced Water Reuse Decision Making Framework (NRC, 2009). [21] The framework is shown below in Figure 8. Based on this framework, the Consortium identified a series of research and analysis efforts to fill gaps in the research and risk assessment elements as shown in Table 6.

[3] Ground Water Protection Council (GWPC). 2019. *Produced Water Report: Regulations, Current Practices, and Research Needs.*
https://www.gwpc.org/sites/gwpc/uploads/documents/Research/Produced_Water_Full_Report___Digital_Use.pdf
[20] NRC, 2009. National Research Council, Science and Decisions: Advancing Risk Assessment, (Washington, DC: The National Academies Press, 2009), p. 68. https://doi.org/10.17226/12209.

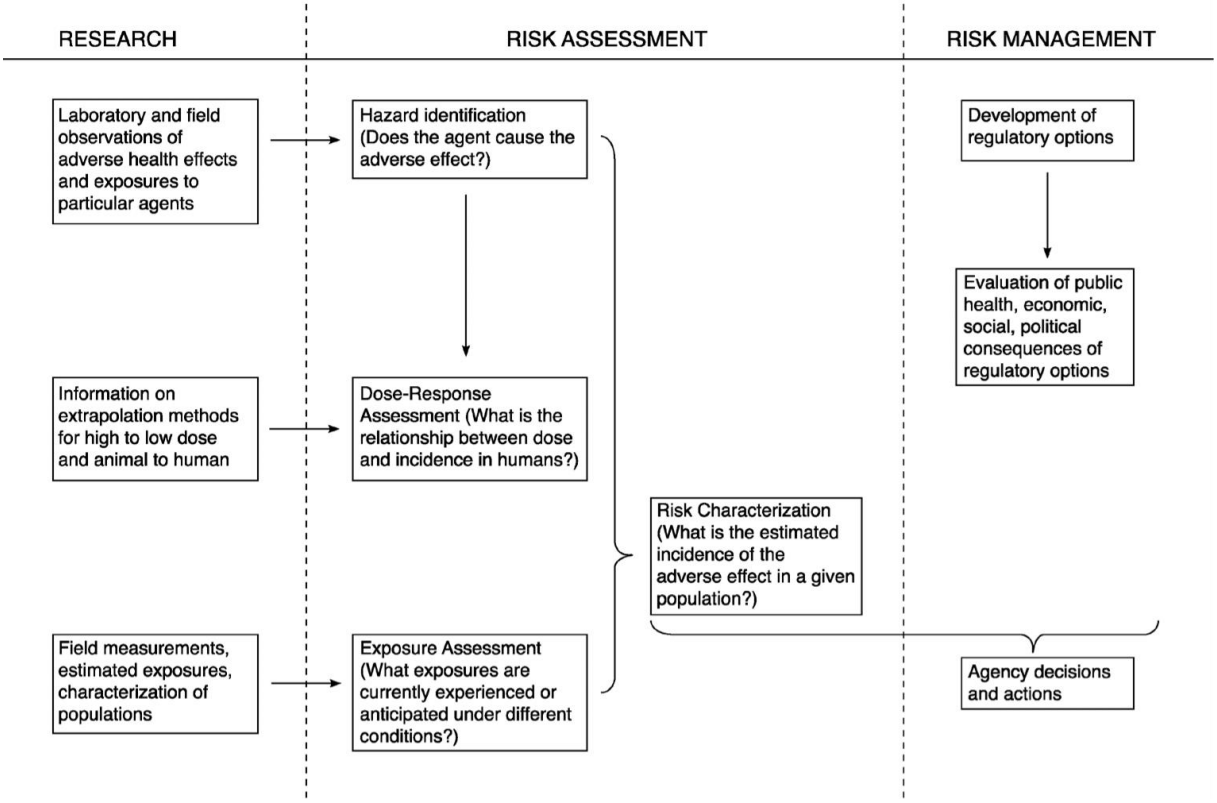

Figure 8. NRC Risk Assessment-Risk Management Framework

The Consortium has identified several areas where contributions can be made to the NRC Framework. The overarching intent is for the Consortium to provide quantitative data relevant not only to treatment effectiveness, but also to health, safety, and risk evaluation. This information can then be used by resource and regulatory agencies for them to make science-based risk decisions and policies. Research is needed in the following areas to support regulatory agency decisions on risk management by providing high-quality data from the treatment testing and analysis:

- constituent identification
- laboratory and field observations
- extrapolation of results to different species
- field measurements of exposures
- hazard identification
- dose-response analysis and exposure assessment.

Require Full Disclosure of all Chemical Additives. The Consortium will require full disclosure of all detected constituents analyzed in the produced water samples, or in treatment data provided to the Consortium. The objective for full disclosure fills a gap in existing laboratory and field observations for the risk assessment framework, and is also important for health and safety evaluations of the treatment testing.

Support state-of-the-art Qualitative and Quantitative Risk Assessment and Toxicology Assessment Methods. The Consortium's independent evaluation of treatment system outcomes is intended to ensure that water and waste product data is of the highest quality achievable. Subsequent risk evaluations and communications using the data will then be reliable. The Consortium will support the use of state-of-the-art toxicological methods being developed by the EPA. For example, the Consortium has provided produced water samples to the EPA in association with the Regional Assessment of Risk and the Environment Project (RARE) to identify chemical hazards and potential risks. These methods incorporate measurement of plant, soil, and ecological uptake of constituents; Whole Effluent Toxicology (WET) testing; Toxicity Identification and Evaluation; hydroponic plant accumulation, ecological accumulation, and soil accumulation studies in controlled greenhouses; and new cell-line risk-testing approaches. The objective is to move beyond simple qualitative screening evaluations, to a more quantitative data collection approach whenever feasible.

Support Fit-for-Purpose Risk Testing. The Consortium will coordinate with the New Mexico Water Resources Research Institute (WRRI), the NM Agriculture Research Centers, the Brackish Groundwater National Desalination Research and project proponents selected through a rigorous RFP process to support not only laboratory but also longer term, field studies on fit-for-purpose produced water reuse. These tests may include greenhouse studies, WET testing, and significant laboratory testing. These efforts are expected to be complex and could impact Consortium progress depending on available funding. However, the results will be valuable contributions to our understanding of treated produced water toxicity and risk, which is critical to inform future science-based reuse regulations, such as standards and monitoring requirements for discharge permits.

Toxicology and Risk Research and Outreach Tasks. Table 6 presents the tasks proposed to address treated produced water toxicology, public safety and environmental risk identified needs. It also shows proposed public education and outreach efforts. The schedule proposed depends on sufficient Consortium funding to support the Testing and Evaluation Program.

Table 6. Public and Environmental Health, Safety, and Risk Tasks and Schedule

Task	Objective	Start	Finish
Establish greenhouse system for produced water evaluations	Procure and install produced water greenhouse toxicology systems	2021	2021
Develop toxicology testing and sampling protocols with EPA	Establish risk and toxicology sampling and evaluation guidance based on whole effluent and cell-line analysis toxicology and risk impacts being established by EPA	2021	2022
Coordinate initial produced water risk and toxicology sampling and analysis	Assess sampling and analysis test results and lessons learned	2021	2022
Coordinate toxicology and risk sampling and analysis for pilot tests	Evaluate toxicology and risk of treated produced water for four 2021 projects	2021	Mid-2022
Coordinate toxicology and risk sampling and analysis for selected 2022 and 2023 pilot projects	Using current and emerging EPA guidelines and approaches noted above, evaluate toxicology and risk of treated produced water for selected 2023 and 2024 pilot projects	2022	2023
Establish Public Health and Safety Outreach Program	Finalize Public Outreach Plan	2020	2021
Establish Public Education Workshops for Information Outreach	Prepare materials and website and conduct several public education workshops each year	2021	2025
Consider use of approach used for produced water to be applied to other non-traditional water resources	Coordinate results with regulatory agencies and public health groups on benefits for public discussions	2021	2023
Establish risk and toxicology database for treated produced water	Inform public of produced water risk and toxicology and relative risk to other waters	2022	2025

4.3 Strategic Program Area (3)-Economic Development, Policy, and Regulations

4.3.1 Produced Water Infrastructure Development

A priority for the Consortium is the gathering of cost data that can be used for economic analysis of produced water treatment systems, and system feasibility. Along with this information gathering effort, the Infrastructure Engineering Working Group has identified several regulatory, policy,

economic development, and work force development factors that are also related to economic analysis and policy development and thus can be addressed as part of Strategic Program Area 3.

Based on discussions and information developed through the Infrastructure Engineering Working Group participants, there was agreement that the major technical issues associated with infrastructure for produced water reuse in New Mexico include:

- Assessing and quantifying current and future produced water volumes, and the expected volumes and transportation infrastructure needed to facilitate treatment.
- Estimating produced water treatment and distribution infrastructure capacity to support reuse in designated regions, including reuse-specific treatment facilities, pipelines, roadways, railroads, electric power, or large storage improvements.
- Locating treatment facilities based on 'system-level' applications and cost effectiveness. This includes a mix of fixed and portable systems, as well as off-site treatment systems.
- Identifying locations of state, federal, and private lands available for treatment, storage, and use of treated produced water; and
- Identifying, locating, and developing infrastructure for new economic sector(s).

The Consortium will evaluate technical information sectors as listed below to help identify the potential scale of the infrastructure needs, the impact on potential applications, and additional non-technical challenges to infrastructure development. This will enable an economic determination as to the feasibility of produced water uses, including where and how these uses would be appropriate.

Evaluate Produced Water Reuse Volumes. The Consortium has gathered data from available produced water data bases in New Mexico to assess the amounts of water generated from conventional and unconventional oil wells and gas wells as shown in Figure 9. Water to oil ratios will also be reviewed. Salt Water Disposal (SWD) water injection volumes and projected volumes are also important to this analysis, because there are other uses of produced water, such as Enhanced Oil Recovery (EOR) and water recycling inside the oil and gas industry, that take up considerable volumes and reduce the volumes of produced water available for treatment and fit-for-purpose reuse outside the oil and gas sector.

An example of some of these issues and the type of analytical results and prediction of produced water quantity and quality trends in the Permian Basin using machine learning techniques are presented below in Figure 9 for the Permian Basin in New Mexico and presented in detail in Jiang et al., 2021. [21] This type of data analysis can be overlaid across multiple metrics to help identify optimum locations for produced water treatment projects for various fit-for-purpose applications or match economic development opportunities with expanded drilling and produced water availability data. The efforts could help establish major economic development opportunities across oil and gas basins in New Mexico based on emerging trends in oil and gas operations.

[21] Jiang, W., Pokharel, B., Lin, L., Cao, H., Carroll, K.C., Zhang, Y., Galdeano, C., Musale, D.A., Ghurye, G.L., Xu, P., 2021. Analysis and prediction of produced water quantity and quality in the Permian Basin using machine learning techniques. Science of The Total Environment 801, 149693.

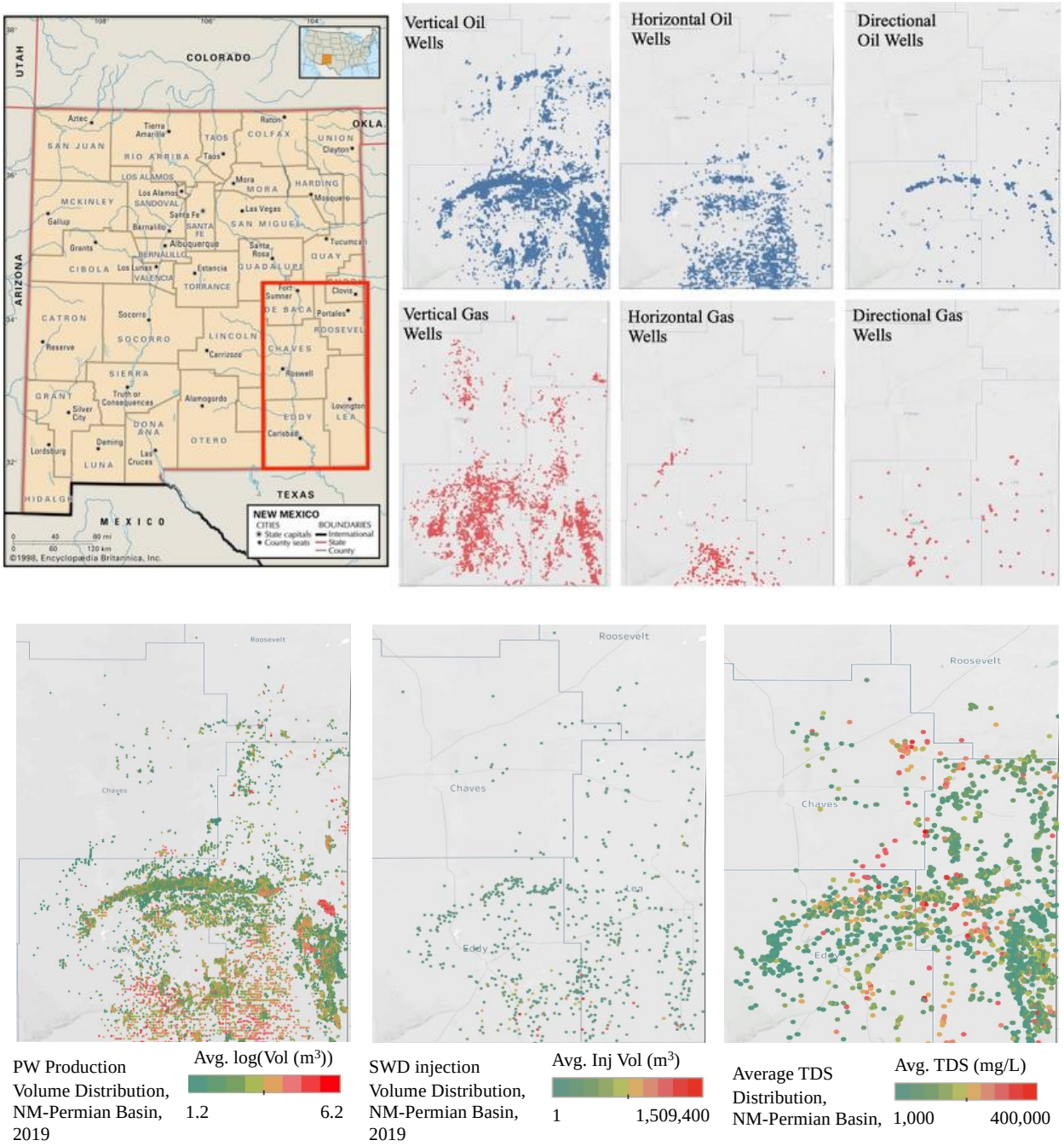

Figure 9. Different types of wells, produced water volume in 2019, saltwater disposal (SWD) wells injection volume in 2019, and average PW total dissolved solids (TDS) distribution in the NM-Permian Basin. [21]

(The red rectangle is the boundary for all graphs. For the volume distribution graph, the unit is log10 (Volume (m^3)). NM county map source: (mapofus, 2021). Graphs from (Jiang et al., 2021) [21]

Projected Produced Water Treatment Infrastructure Needs. The Consortium will evaluate different types of infrastructure that can be used for, or adapted to, the treatment and reuse of produced water. These include fixed treatment facilities, pipeline gathering systems, pretreatment facilities, and mobile treatment systems.

The Consortium will use the infrastructure data to identify potential treatment and reuse locations. A GIS system will be used to optimize the coordination of different fit-for-purpose options and produced water quantity and quality availability. This would need to be integrated with GIS data infrastructure such as pipelines, electric power, brackish aquifer data, available rights-of-way, etc., to help organizations and private companies assess different produced water reuse opportunities. The GIS should include state and federal public lands and private lands and current and projected produced water availability by township. Previous work by WRRI is a good example of this type of analysis. [22]

The Consortium has already started efforts with federal land management agencies to use their GIS systems to track right-of-way and federal lands needing restoration using an ArcGIS system and integrated into GIS layers in the NM Produced Water Data Portal. Additionally, the Consortium is working with the New Mexico Petroleum Recovery Research Center at New Mexico Tech and the GWPC to upgrade the New Mexico produced water quantity and quality data base to a web-based system that should be in operation for public use in late 2021.

4.3.2 Regional Socio-Economic Development Modeling and Planning

The use of produced water to support new and current industrial sectors in New Mexico may be feasible and supports the intent of the legislation and MOU. This could include agricultural and industrial manufacturing facilities and other types of companies. A few examples that have been discussed within the state include pumped hydro energy storage to support renewable energy development, chlor-alkali plants to create acids and bases for the oil and gas industry and other industries, glass manufacturing for solar panels and wind turbine composites, plastics manufacturing, and mineral recovery including rare earth elements, heavy metals, radionuclides, and special compounds for pharmaceuticals, as well as solution mining.

Establishing an industrial sector where the raw materials are not concentrated but distributed across a vast landscape in low concentrations may require additional planning and infrastructure and have social or health and safety risks. This could include large pipelines, upgrades to rail lines, improved connections to electric power infrastructure, etc. This type of planning, coordination, and support is something not often developed ad hoc at the local level, but requires state economic development, regulatory, and policy support to create the economic vision and support the infrastructure development needed, as well as coordinate integration with the oil and gas sector and the state oversight departments. The Consortium will coordinate with state agencies and research groups to evaluate the economic, social, ecological, and health and safety risks and feasibility of fit-for-purpose reuse of treated produced water.

[22] New Mexico Water Resources Research Institute. Produced Water Web-Mapping Applications. https://nmwrri.nmsu.edu/produced-water-2/maps/

Non-technical Infrastructure Challenges. Some of the regulatory, policy, economic development, and workforce development factors that could impact the development and operation of infrastructure include:

- Coordination of regulatory oversight and jurisdiction of co-located or integrated water pre-treatment (likely at disposal wells with OCD jurisdiction) and treatment plants;
- Workforce development and workforce training for water treatment technicians and operators;
- Support for local economic development to leverage oil and gas and mid-stream investments for efforts to treat and reuse produced water outside the oil and gas sector;
- Evaluate the feasibility of state and local economic development policies to support new industrial sectors possible through the treatment and reuse of produced water; and
- Feasibility for infrastructure needed such as pipelines, transmission lines, railroad improvements, highway improvements, and airport improvements needed for sectors such as: mineral recovery, renewable energy storage, and renewable energy manufacturing, among others.

Infrastructure Research and Development Schedule. Table 7 provides a timeline for the Consortium to tasks addressing infrastructure research and development:

Table 7. Infrastructure Research and Development Tasks and Schedule

Task	Objective	Start	Finish
Produced water Infrastructure and use GIS database development	Web-based use and infrastructure GIS data base initiated	Mid -2021	2022
Infrastructure GIS system expansion and upgrades	Phase II GIS Improvements/Upgrades	2022	2023
Updated produced water quality and quantity database	Web-based NM (WaterStar) Produced Water Data Portal Activated	Mid- 2021	2022
Infrastructure needs assessment with scenario planning	Workforce training program evaluated	2022	2023
Produced water treatment workforce development	Workforce training program development and coordination	2023	2024
Coordination and integration with NM Economic Development Department	Local and state economic sector and industry recruiting, legislation, and state and local IDB funding	2022	2022-2030

4.4 Public Education and Outreach

A program to provide information and education to the public concerning NMPWRC activities and progress must be designed to help identify and address concerns associated with the use of industrial wastewater like produced water and further inform the NMPWRC's research agenda over time. NMED's summary of public input gathered via email and outreach meetings in the fall of 2019 includes:

- Public concern or opinion is roughly split between regulation needs and research needs, with slightly more focus toward regulatory matters (59% or 1,350 out of 2,296 statements);
- Most input (56% or 1,278 out of 2,296 statements) generally expressed concern regarding the unknowns surrounding produced water use outside of oil and gas, how these unknowns may inhibit the development of safe and effective regulations, and how these potential negative implications may affect human health and the environment, now and in the future;
- Six percent of comments expressed direct support for one or more produced water topics, while 38% of comments conveyed opposition to one or more produced water topics.

For a more detailed summary of public input, see: https://www.env.nm.gov/new-mexico-produced-water/public-participation-2/.

Science-driven and public health-based education and outreach will be the foundation of discussing fit-for-purpose treatment and reuse of produced water. Realizing the need to inform and educate the public on the benefits and impacts of produced water reuse, the Consortium established a comprehensive Consortium **Communication, Outreach, and Education Plan** as noted in NMPWRC 2020.

Implementation of this Plan involves a combination of activities and approaches, including:

- Use of web-based communications and document management to provide Consortium members and the public easy access to information on Consortium efforts and activities;
- Internal communication processes and approaches to assist Consortium members in tracking Consortium progress, activities, meetings, schedules, technical and scientific research opportunities, research activities, and summary research reports;
- External communication of Consortium operations, activities, highlights, research, and reports for public review;
- Outreach to the public through educational programs to improve public understanding of the implication of research results in terms of expected impacts to public and environmental health and safety for fit-for-purpose reuse of treated produced water; and
- Recognition that educational and outreach programs and workshops need to be varied and geographically distributed across New Mexico to solicit input from a diverse spectrum of social, economic, cultural, ethnic, and aged segments of our communities.

Communication strategies will be based on an evaluation of prior and current communication efforts, with an emphasis on input from previous public meetings. Communication events or topics shall include built-in feedback opportunities, such as questionnaires or website feedback. The Consortium will also receive feedback through a general email at nmpwrc@nmsu.edu, which will

be monitored and integrated on an on-going basis. This information will be used by the Consortium to continuously improve public education and outreach activities. Progress toward meeting objectives will be evaluated at regular intervals, so the process and approaches can be adjusted accordingly.

5. Anticipated Research Outcomes

The Consortium's science and technology research, development, testing and evaluation efforts have been designed to fill current and emerging science and technology gaps for the fit-for-purpose reuse of treated produced water for uses outside the oil and gas sector. The gaps identified and receiving the most emphasis in this research plan include:

- the collection and development of more detailed produced water quality data and the use of more robust water quality analysis systems;
- support for research on emerging innovative produced water treatment approaches and collection of more operational produced water treatment technology cost and performance data to facilitate technology implementation;
- establishing more appropriate and detailed risk and toxicity methods for assessing treated produced water toxicity and risk to human and environmental health and safety for various fit-for-purpose produced water reuse applications;
- quantifying the cost/benefit/risk issues and tradeoffs associated with fit-for-purpose - treatment and reuse of produced water; and
- providing information in a form that will allow New Mexico environment and natural resource management agencies to establish science-based policies and regulations to safely and effectively oversee discharge, handling, transport, storage and recycling or treatment of produced water and co-products for various reuse applications.

The research and development efforts identified focus on reducing many of the classic technical, economic, risk, and public awareness barriers to the development, adoption, and use of new or innovative technologies. A key component of these efforts includes involving and informing government, industry, academia, and environmental and community advocates of the efforts and progress in the assessment, evaluation, and verification of innovative produced water analysis and treatment technologies by the Consortium as an independent evaluation group that adheres to the highest standards of scientific integrity.

At a high level, the efforts identified in this Gap Analysis and Research Plan address the following issues of the use of treated produced water for fit-for-purpose use: 1) the technical, cost, and engineering risks, 2) the public and environmental health and safety risks, 3) support for reducing fresh water use and improving fresh water supply sustainability under emerging climate conditions, and 4) timely dissemination of research results to inform and educate the public,

industry, and government agencies on the viability of the treatment and reuse of produced water for fit-for-purpose uses outside the oil and gas industry.

The proposed research effort is broad and will require significant funding to accomplish. Under current funding of less than $1 million per year, the efforts noted above will not be fully completed until 2025. With further funding reductions, these efforts will take significantly longer. With increases in funding and support from legislators, sponsors, collaborators, and agencies to $3 million per year, the program can be significantly accelerated and be completed by the end of 2024.

6. Appendices

Appendix A – References for Literature Review

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