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Jurisdictional Review of Regulations and Practices Which Enable Economic Water Recycling in Hydraulic Fracturing (HF)

Disclaimer:

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- Representatives from four U.S. states with expertise in hydraulic fracturing and their respective water management regulatory frameworks – Interview participation (in-kind).

Publicly available resources were consulted in preparation of this report. Information provided by project participants and industry contacts has been aggregated and anonymized to maintain confidentiality.

Executive Summary

This report, prepared by WaterSMART, a Hazen Company, provides an in-depth comparative analysis of regulatory and operational practices for produced water recycling across key hydraulic fracturing jurisdictions in North America: Alberta, Pennsylvania, New Mexico, Texas, and Colorado. While the core stages of water management (i.e., sourcing, use, recovery, disposal, and recycling) are common to all jurisdictions, execution differs with local geology, produced water chemistry, infrastructure availability, and regulatory frameworks.

The analysis draws upon interviews with producers and jurisdictional representatives, academic literature, and publicly available resources. Its results highlight key practical (i.e., disposal capacity, seismicity, arid climate) and regulatory differences which drive produced water recycling in the U.S. while it remains limited in Alberta. Alberta's comparatively lower rates of produced water recycling are attributable to a complex interplay of boundary conditions, including but not limited to regulatory frameworks and provisions.

Additionally, this study's findings reveal a potential shift in hydraulic fracturing (HF) water management, where produced water is being reclassified from disposal liability to strategic asset. Key findings from the comparative analysis include:

- In Pennsylvania's Marcellus Formation, produced water has similar salinity and water-oil ratios to Alberta's Montney and Duvernay formations. Despite these characteristics, limited in-state disposal and costly interstate transport have pushed producers toward closed-loop produced water recycling.
- In the Permian Basin (New Mexico and Texas), induced seismicity limitations on disposal, coupled with an arid climate and high water-oil ratios, is shifting economics toward produced water recycling as a competitive alternative to high-quality nonsaline (HQNS) water, even though produced water salinity is broadly comparable to that of the Montney and the Duvernay.
- Colorado stands out with recently mandated recycling and alternative water sourcing targets, as well as a water credit-trading program linked to future drilling approvals. In the arid Niobrara Formation, where produced water-oil ratios resemble Alberta's formations and HQNS water sourcing is more difficult, these rules are expected to further incentivize recycling.
- New Mexico, Texas, and Colorado have legislated or initiated Produced Water Consortiums, developed in partnership with universities, government agencies, and industry. These consortiums are designed to encourage produced water recycling and to address regulatory, technical, and operational barriers to its broader use. The consortiums conduct research, sponsor pilot programs, and provide policy

recommendations aimed at improving produced water recycling within the oilfield and evaluating opportunities for the safe recycling of treated produced water outside the oilfield.

- A key distinction in Alberta's Duvernay and Montney formations is the prevalence of highly sour produced water. Combined with the general availability of HQNS water and deep-well disposal capacity, this has limited the deployment of large-scale produced water recycling compared to the U.S. jurisdictions.

The figure below depicts the relative ranking of four primary characteristics influencing the degree of produced water recycling by jurisdiction, based solely on available formation-level data for total dissolved solids (TDS), H_2S concentration, Water-Oil Ratio, and HQNS Water Sourcing Limitations. A higher score suggests a stronger theoretical potential for produced water recycling, regardless of each jurisdiction's regulatory framework, HQNS water stewardship, or any constraints related to produced water recycling. Producers operating within these formations may encounter site-specific conditions that deviate from the reported figures.

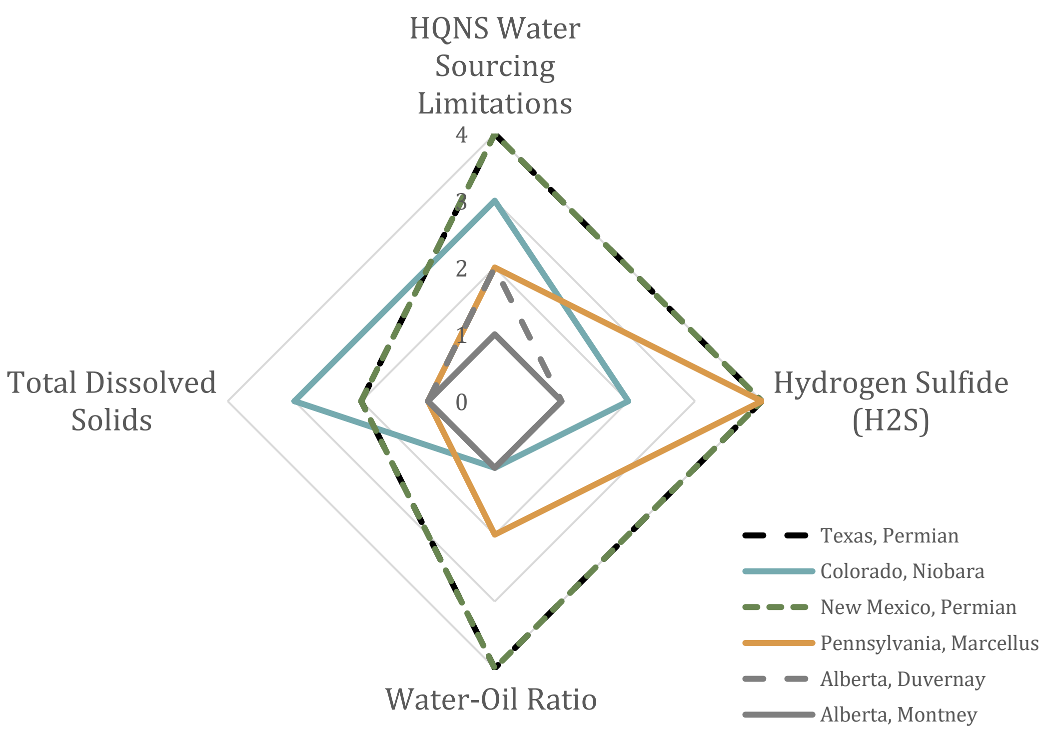

Figure A. Radar chart for quantitative evaluation of produced water recycling potential.

Informed by research, interviews, and analysis, the activities below are recommended to further reduce the barriers to produced water recycling in Alberta:

1. Engage the Alberta Energy Regulator (AER) on regulations that most materially influence the economics of produced water recycling, particularly the storage capacity and duration limits set by AER D055 and the blending requirements during storage outlined in AER D058 and the Waste Control Regulation.
    a. AER D055: Increasing the allowable capacity and storage duration of Aboveground Wall Storage Systems (AWSSs) would enable producers to accumulate sufficient volumes for new fracturing operations, while also providing the operational flexibility needed to facilitate future produced water sharing between operators. Additionally, primary and secondary containment requirements for AWSSs and Engineered Containment Ponds (ECPs) could be updated to reflect best practices observed in other jurisdictions while reducing overall costs for implementation.
    b. AER D058 and Waste Control Regulation: Both the Waste Control Regulation and D058 do not allow for dilution of waste by adding any solid or liquid to avoid regulatory requirements.
        i. Co-developing a risk-based protocol for the safe storage of blended water which incorporates monitoring, tracking, and emergency response plans, would further enable the accumulation of meaningful produced water volumes for recycling.
    c. Proposals to amend both directives and regulation could leverage performance data from produced water impoundments in Colorado, New Mexico, and Texas, along with secondary containment practices used in Colorado, New Mexico, Texas, and Pennsylvania, to develop Alberta-appropriate safeguards that support larger on-site or centralized storage for produced water, including blends.
2. Create a shared, voluntary, anonymized data and industry-led benchmarking program for produced water.
    a. The program's purpose is to support decision-making and risk-screening, including identification of sites where produced water recycling is not viable. A data-sharing program would allow producers to monitor aggregated peer data and identify produced water composition trends, recovery volumes, and shared challenges.
        i. Access to broader produced water composition datasets could support assessments of formation chemistry compatibility and help both

producers and water management midstreamers evaluate the feasibility of centralized recycling hubs and fit-for-purpose treatment technologies.

b. The proposed initiative would be governed independently from regulatory compliance reporting requirements and would not to be used for enforcement.

    i. Sharing similarities with this approach, the AER Water Use Performance report provides company-level HF produced water use data, but it does not provide water quality, is not anonymized, and is part of regulatory compliance.

3. Leverage data sharing and benchmarking program's data to coordinate industry-led bench-scale, pilot-scale, or field-scale pilots and develop H_2S and salinity treatment technologies under Alberta-specific conditions. Pilot results, including ranges for capital and operating costs and produced water quality outcomes, would be shared between participants.

    a. The AUPRF, funded voluntarily by over 300 producers through an annual levy, supports applied research by universities, operators, and consultants to address high-priority environmental issues facing the upstream industry. The AUPRF operates as an industry-led counterpart to the Produced Water Consortiums established in the United States and could be leveraged to develop produced water H_2S and salinity treatment pilots.

        i. Under the Water Innovation Planning Committee (WIPC), AUPRF has recently issued a request for proposal on produced water treatment in H_2S environments in pilot phase.

    b. Other similar initiatives have taken place in Alberta, including the Canadian Emissions Reduction Innovation Consortium (CanERIC), led by Petroleum Technology Alliance Canada (PTAC), and the Water Technology Development Centre (WTDC). In both cases, industry guided the work, with Alberta Innovates contributing a portion of the funding.

        i. CanERIC uses an industry-driven platform to identify key challenges and test new technologies to address and reduce risks associated with methane emissions through coordinated lab and field trials with academic and institutional partners.

        ii. The WTDC was a joint venture by Suncor Energy Inc., Canadian Natural Resources Limited, Cenovus Energy, and the China National Offshore Oil Corporation, supported through funding from Alberta Innovates'

Clean Technology Facilities Support Program and Water Innovation Program.

4. Integrate water lifecycle considerations into producers' economic models.
    a. Existing economic models may not fully account for the complete water lifecycle in HF operations, which can make produced water recycling appear more costly than current water management practices. To address this gap, AUPRF could facilitate the development of standardized economic models that consider all stages of the water lifecycle, including risk-adjusted costs such as probability-weighted production impacts, regulatory risk, disposal constraints, and reputational exposure.
        i. Incorporating producer input, including the sharing of operational data and best practices, would support more robust model calibration and enable a more accurate valuation of water across its full lifecycle, beyond capital and operating expenditures.

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1. Introduction

Alberta's Water Conservation Policy for Upstream Oil and Gas Operations (WCP) articulates a preference for the use of alternative water sources over high-quality nonsaline (HQNS) water sources, including the recycling of produced and flowback water in hydraulic fracturing (HF) (i.e., produced water recycling) [1]. In 2024, WaterSMART | A Hazen Company (WaterSMART) conducted a study with funding from the Alberta Upstream Petroleum Research Fund (AUPRF) to identify the barriers to produced water recycling and categorize them according to which step in hydraulic fracturing operations they most directly impact. The study revealed that economic factors connect all the identified barriers to produced water recycling and highlighted the need for further research to better address them.

Building on previous research, this report presents a systematic review of regulatory and operational practices which both enable and constrain produced water recycling across several North American jurisdictions. Additionally, the report provides a detailed comparison of these practices with those in Alberta throughout the HF water management lifecycle shown in Figure 1. Figure 1, adapted from WaterSMART's 2024 report, includes details for the "Extra Step" of preparing produced water for recycling (i.e., access, storage, conveyance, and treatment), to enable its reintegration at the beginning of the cycle for recycling.

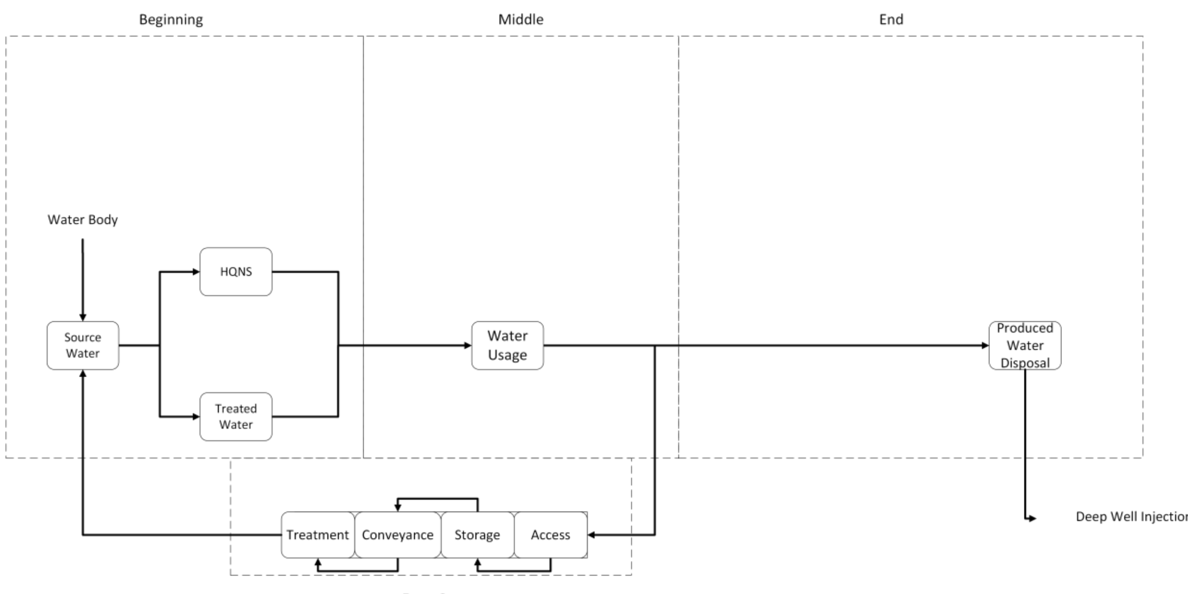


Figure 1. Water management lifecycle for typical HF operations. The process includes sourcing to disposal, along with additional stages for produced water recycling.

By examining each phase of the water management lifecycle in detail, the study identifies combinations of regulatory and operational conditions that may facilitate enhancements in both the economic viability and practical execution of produced water recycling programs in

Alberta. Supporting data for this report was gathered from public databases, interviews with Alberta producers, and engagement with representatives from the other jurisdictions.

1.1 Report structure

This report includes the following sections:

- **Section 2.0** examines the selection of four U.S. jurisdictions of analysis: Texas, Colorado, New Mexico, and Pennsylvania.
- **Section 3.0** outlines the data sources used in this study.
- **Section 4.0** summarizes the policy and regulatory context for HF in Alberta and documents the current state of water recycling for HF in Alberta as of late 2025, as communicated by producer interviewees and the Alberta Energy Regulator (AER) Water Use Performance Report.
- **Section 5.0** presents the quantitative and qualitative frameworks used to compare water management and produced water recycling practices in Alberta and the four U.S. jurisdictions.
- **Section 6.0** details the results of the qualitative and quantitative jurisdictional comparisons.
- **Section 7.0** discusses the combinations of operational, environmental, and regulatory water management practices from other jurisdictions that can be applied to Alberta to improve the economics of produced water recycling.
- **Section 8.0** highlights actionable recommendations that Petroleum Technology Alliance Canada (PTAC), producers, and policymakers can undertake to enable broader adoption of produced water recycling in Alberta.

2. Project Scope

As noted, this report examines both the practical and regulatory influences on the economics of produced water recycling in Alberta, offering comparisons to four U.S. jurisdictions: Pennsylvania, New Mexico, Texas, and Colorado (Figure 2). These jurisdictions were selected based on several factors, including:

- Total HF oil and gas production and produced water recycling rates.
- Variety of regulatory philosophies, from risk-based and incentive-driven models (e.g., Colorado and Texas) to prescriptive frameworks (e.g., Pennsylvania).
- Accessibility to public regulatory documents, performance data, and industry contacts.
- Recommendations from the Water Innovation Planning Committee, convened by PTAC.

Together, these selection criteria provide a representative cross-section of conditions relevant to produced water management. Although it shares shale gas plays with Alberta, British Columbia was not included in the comparison because its context is well understood and has been documented in previous studies [2].

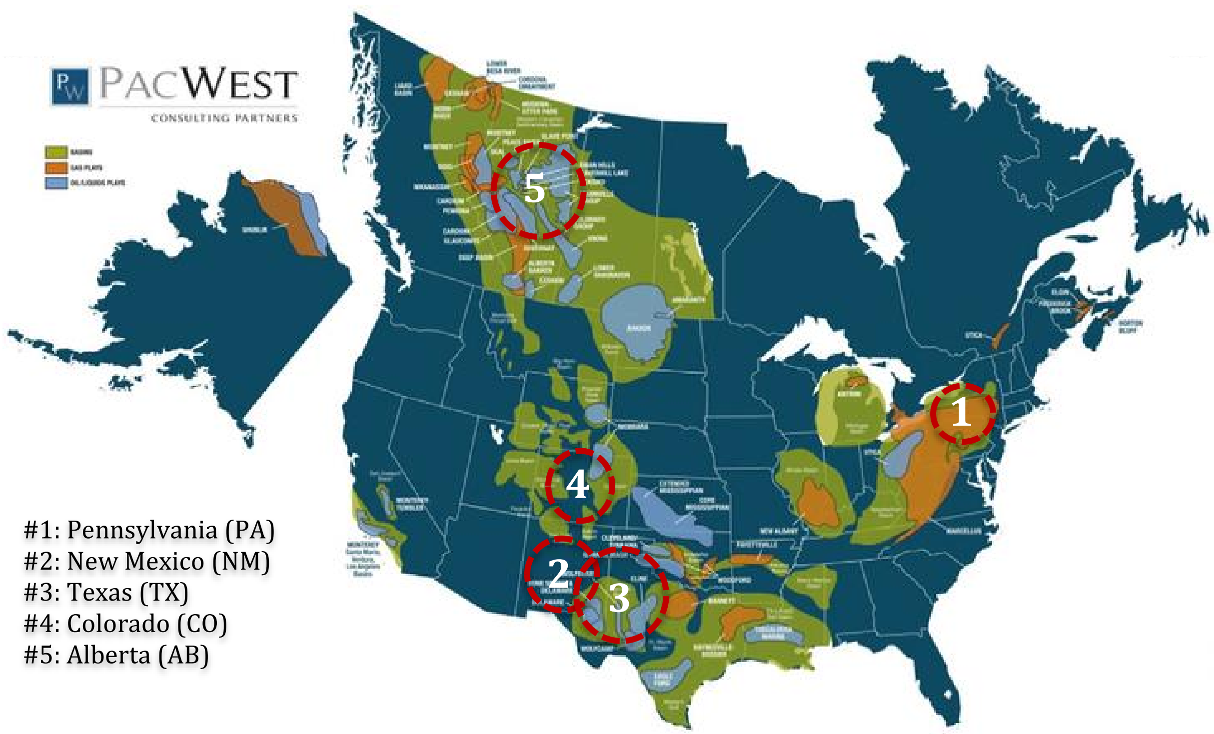


Figure 2. Map of North American shale plays with jurisdictions of interest highlighted [3].

The jurisdictions examined in the study comprise several of North America's most prominent shale formations (Table 1), each characterized by distinct geological attributes that influence water management strategies.

Table 1. Shale formations of interest.

Jurisdiction	Shale formation
Pennsylvania	Marcellus Formation
Texas	Permian Basin
New Mexico[1]	Permian Basin
Colorado	Niobrara Formation
Alberta	Duvernay Formation
	Montney Formation

Pennsylvania's Marcellus Formation, part of the Appalachian Basin, is one of the largest shale gas plays in North America. HF operations in Pennsylvania are characterized by high recycling rates, driven by regulatory limits on disposal [4]. Upwards of 80% of produced water in Pennsylvania is recycled in HF operations [4, 5].

The Permian Basin, which extends across Texas and New Mexico, consistently ranks high in both salinity and produced water recovery volumes, presenting challenges for treatment and disposal [6, 7]. Disposal in the region is constrained due to seismicity risks, prompting regulators to enforce volume limitations and suspend the operation of some deep-well injection wells. The potential for recycling is considerable and continues to expand, largely as a result of elevated disposal costs for existing produced water volumes and significant investments in supporting infrastructure [8, 9, 10].

Regulatory requirements in Colorado are expediting the adoption of produced water recycling, including phased recycle targets starting at 4% by 2030. These initiatives establish Colorado as a leader in policy-driven HQNS water conservation efforts [11, 12]. Colorado's resource development is primarily focused on the Niobrara Formation within the Denver-Julesburg Basin, which is characterized by moderate salinity and lower produced water recovery volumes relative to other formations like the Permian [13].

[1] Texas and New Mexico share the Permian Basin, offering an opportunity to assess how varying regulatory and operational frameworks impact water management practices within a shared geological context.

3. Data sources

Several data sources, summarized below, were utilized to prepare this report, including jurisdiction-specific regulatory frameworks, industry data sources, and academic literature.

3.1 Jurisdiction-specific regulatory frameworks

WaterSMART reviewed each jurisdiction's regulatory framework to identify requirements, incentives, and barriers related to water sourcing, recycling, storage, conveyance, and disposal in HF operations (Figure 1). These documents provided the foundation for comparative analysis and informed the scenario modeling and recommendations in this report. Table 2 summarizes several critical, overarching regulations and policies pertaining to produced water recycling in the selected jurisdictions. Certain regulations and policies are not analogous across all regions; this is discussed further in Section 6.

Table 2. Relevant regulation and policy documents in selected jurisdictions.

Jurisdiction	Regulatory Frameworks	Key Focus Areas
Pennsylvania (PA)	Department of Environmental Protection (DEP) Regulations (Chapter 78 Oil and Gas Wells and Chapter 95 Wastewater Treatment). Clean Streams Law. Act 13 of 2012. DEP Technical Guidance.	Water management for oil and gas. Wastewater treatment. Recycling standards. Environmental compliance.
New Mexico (NM)	Oil Conservation Division (OCD) Rules (19.15.34 NMAC Produced Water Management and 19.15.29 New Mexico Administrative Code Injection and Disposal). Produced Water Act. New Mexico Environmental Department (NMED) Guidance.	Produced water management. Disposal and injection standards. Environmental compliance.

Jurisdiction	Regulatory Frameworks	Key Focus Areas
Texas (TX)	Texas Railroad Commission Rules (Statewide Rules 8, 9, and 46). Texas Water Code. Texas Commission on Environmental Quality (TCEQ) Guidelines. Produced Water Consortium Reports.	Water protection. Fluid injection. Produced water recycling. Regulatory compliance for recycling.
Colorado (CO)	Colorado Oil and Gas Conservation Commission (COGCC) Rules (907 and 908). Colorado Water Quality Control Act. Colorado Department of Public Health and Environment (CCDPHE) Guidelines.	Waste management. Produced water recycling. Water quality protection.
Alberta (AB)	*Water Act.* Water Conservation Policy for Upstream Oil and Gas Operations. Alberta Energy Regulator Directives (D077, D055, D058, and D051). *Oil and Gas Conservation Act*. *Environmental Protection and Enhancement Act*.	Water sourcing and conservation. Storage and disposal requirements. Pipeline conveyance. Injection and disposal wells. Environmental protection.

3.2 Industry data sources and academic literature

The report leverages industry data, performance metrics, and academic literature to assess the current state and economic potential of produced water recycling in HF. These metrics provide quantitative evidence to support scenario comparison, benchmarking, and recommendations, with sources including:

- AER's 2024 Water Use Performance Report.
- Jurisdictional Performance Metrics:
    - Publicly available datasets and reports obtained from industry regulatory agencies in Texas, Colorado, Pennsylvania, and New Mexico facilitated cross-

jurisdictional comparisons of recycling rates, water use intensity, and key cost drivers.

- Direct producer and jurisdictional representatives' input (i.e., interviews):
    - The information obtained through interviews was used to validate both quantitative and qualitative results, ensuring that the report's conclusions are firmly based on practical experience and subject-matter expertise from various jurisdictions. See further information in Section 3.3.
- Peer-reviewed articles, technical papers, and conference proceedings:
    - Peer-reviewed literature informed the chemistry of produced water in the selected formations and recent advancements in produced water treatment, recycling, and disposal capacity in the analyzed jurisdictions.

3.3 Interviews

WaterSMART conducted six interviews with representatives of HF producers operating in Alberta. Interviewees offered a range of insights on water management practices and produced water recycling, with a focus on the operational, environmental, and regulatory factors that impact the economic viability of produced water recycling for their unique circumstances in Alberta. Interviewees were selected based on the proportion of their total water consumption that was met by alternatives to HQNS water, including produced water recycling. The interview questionnaire comprised both core questions and supplementary prompts, facilitating comprehensive discussion of the following themes:

- Water management approach:
    - Description of each producer's overall strategy for sourcing, using, and disposing of water in HF operations, including details on the types of water sources used (e.g., HQNS, saline, or recycled) and methods for storage and transportation.
- Experience with produced water recycling:
    - Reflection on successes, challenges, and key takeaways from current or past produced water recycling efforts.
- Drivers and barriers:
    - Identification of the main factors motivating or impeding produced water recycling, such as cost, technological advancements or limitations, stakeholder expectations, and infrastructure constraints.

- Regulatory and policy environment influence on water management in Alberta and other jurisdictions:
    - Assessment of regulatory and policy impacts on water sourcing, treatment, and disposal practices as they relate to produced water recycling.
- Future outlook:
    - Compilation of perspectives on anticipated trends, opportunities, and challenges for produced water recycling (e.g., new technology pilots).

A copy of the interview questionnaire is included in Appendix A.

In addition to gathering insights from Alberta producers, WaterSMART executed interviews with subject matter experts representing each of the four U.S. jurisdictions. These interviews explored the current operational paradigms of produced water recycling in each location and delineated state and formation-specific geological conditions and historical developments that have contributed to higher produced water recycling rates compared to Alberta. Notable factors such as statutory and regulatory requirements, process constraints, and economic drivers were assessed using both quantitative and qualitative methods through a matrix-based framework, as further described in Section 5.

4. Alberta Regulatory Environment and Water Management Overview

Alberta’s regulatory environment sets the context within which HF operators assess and implement produced water recycling. Section 4.0 summarizes Alberta's existing regulatory framework, details the current state of produced water recycling in HF operations, and presents key findings from the interviews conducted with six Alberta producers.

The full scope of the regulatory regime for water management in Alberta includes a combination of provincial regulatory instruments which vary in type, level of authority, and enforcing body, ranging from statutes to policy and specific directives. At a high level, water resources in Alberta are governed through the *Water Act*, which aims to balance the competing water needs of people, the environment, and industry. Additionally, the *Water Act* sets out how water licences are issued and administered, including the rules that guide regulatory decision-making [14]. Additionally, the province of Alberta developed the Water for Life Strategy, which provides a framework to guide province-wide water management [15].

The WCP, issued in December 2020, introduces specific water policy direction for oil sands mining, thermal in situ and enhanced oil recovery operations, and multi-stage HF operations. The WCP’s goal is to ensure reliable and good-quality water supply to support a sustainable economy, as envisioned in the Water for Life Strategy, while managing water allocations for upstream oil and gas operations in a way that is consistent with the purpose of the *Water Act.* The WCP articulates a preference hierarchy for alternative water sources (e.g., produced water, municipal effluent, saline groundwater) over HQNS water where it is technically and economically feasible, while requiring producers to evaluate environmental net effects and cumulative impacts associated with different water sourcing scenarios [1].

Recently, the Water Use, Management, and Conservation Bulletin, issued on May 14, 2025, reinforced the WCP expectations for using alternative nonsaline water sources to reduce reliance on HQNS water. Additionally, the bulletin emphasized that industry should be aware of active water shortage advisories and plan accordingly when applying for a temporary diversion licence[2] under the *Water Act* [16]. For more details on AER-specific manuals and directives related to produced water, refer to Appendix B.

[2] A temporary diversion licence (i.e., TDL) is defined as an authorization that allows a water licence holder to temporarily divert and use surface water or groundwater in Alberta for a period of up to one year. TDLs are frequently used for drilling oil and gas wells [112].

4.1 Produced water recycling landscape

Produced water recycling in Alberta remains relatively uncommon compared to many other North American jurisdictions. This section provides an overview of the province's current produced water recycling landscape, drawing on water use performance data, interviews with industry representatives, and recent published studies to establish a baseline understanding of the practice.

4.1.1 Water use trends in HF (AER Water Use Performance Report)

The Water Use Performance Report is an annual publication by the AER that provides information about water allocation and use for four oil and gas extraction technologies: oil sands mining, in situ oil sands, enhanced oil recovery, and hydraulic fracturing. Figure 3 presents the aggregate water usage in HF operations within Alberta, categorized by water type. The HQNS water volume is indicated on the secondary vertical axis, whereas volumes for all other water types are displayed on the primary vertical axis.

The past decade has seen a modest increase in the volumes of produced water recycled for HF. While the growth in recycled water usage remains limited, the overall trend for all alternative water sources combined is more favourable [17]. Despite direction from the WCP to decrease reliance on HQNS water for hydrocarbon production, Alberta primarily uses HQNS water for HF[3], more so than other jurisdictions, as discussed in further detail in Section 6.0.

[3] Notably, the ratio of HQNS water barrels per barrel of oil equivalent produced has nearly halved in the same period, indicating a decreasing trend in HQNS water use intensity. According to the latest edition of the report (i.e., 2024), released in October 2025, nonsaline water use in HF is approximately 0.65 barrels of water per barrel of oil [111].

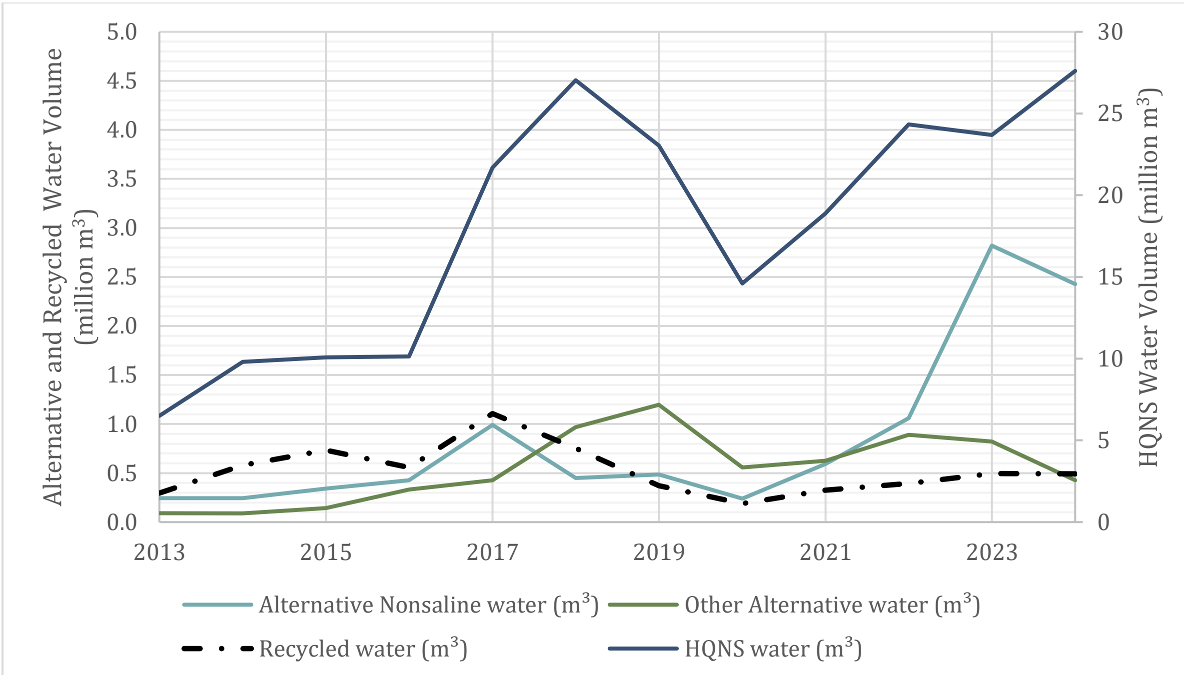


Figure 3. Total water use in HF operations in Alberta by type (2013-2024) [17].

4.1.2 HF producer interviews

As outlined in Section 3.0, six interviews were conducted with HF producers operating in Alberta, each with varying degrees of produced water recycling and use of other alternatives to HQNS water. This subsection presents the principal themes and key highlights from the interviews with HF producers, offering insight into their perspectives and practices regarding produced water recycling in Alberta. Several elements addressed in the interviews are recurring across the themes outlined below, including factors driving produced water recycling and the impact of regulatory and policy frameworks on water management.

4.1.2.1 General water management practices and water sourcing

Interviewees summarized their water management practices, emphasizing their approach to water sourcing for HF operations. Consistent with previous findings (i.e., WaterSMART's 2024 report) and the AER's Water Use Performance Report, producers in Alberta have continued to primarily utilize HQNS surface water. The primary enabler for this approach is Alberta's relatively accessible surface water supply, particularly within the Montney Formation. Although river flows can be intermittently low in parts of Alberta, some interviewees have existing HQNS water storage infrastructure to mitigate the impacts of supply variability and enable the primary use of HQNS water. Additionally, all interviewees outlined the comparatively lower cost of storage for HQNS water compared to produced water.

Some operators have supplemented their HQNS water with alternative water sources, including produced water, aligning with the recommendations of the WCP. Among producers who do not, the willingness to explore alternatives to HQNS water remains strong as a means to enhance water security in the long-term, provided that the associated costs are compatible with their operational requirements.

4.1.2.2 Recent experience with produced water recycling

Interviewees described recent examples of produced water recycling initiatives their companies have undertaken and the challenges they faced during implementation and scale-up. All interviewees have explored the opportunity to increase produced water recycling rates, with several advancing pilot projects that achieved positive outcomes at limited operational scales, and in some cases, progressed into full-scale operations. However, most interviewees indicated that their efforts to expand these initiatives to larger operational volumes were constrained by elevated storage and conveyance costs associated with handling greater quantities of produced water, as well as a heightened risk profile that deterred further scale-up (see more on barriers below).

When interviewees were asked about the primary drivers for their produced water recycling initiatives, the majority cited environmental performance and internal sustainability goals. Notably, one interviewee shared that alternative water usage is a fundamental standard of their operations as they work towards reducing their reliance on HQNS water. Most interviewees did not view the WCP, in and of itself, as a primary driver of increased produced water recycling; one noted that it has not significantly influenced their decision-making to date. Interviewees acknowledged that producers who prioritize produced water recycling (and other alternatives to HQNS water) will have additional flexibility to address potential future challenges related to HQNS water availability.

4.1.2.3 Barriers – Cost, risk, and regulations

The third area of discussion centered on producer-specific barriers to increasing produced water recycling rates. All interviewees consistently identified overall cost as the predominant barrier to expanding recycling operations, consistent with findings from WaterSMART's 2024 report. Specifically, the sour nature of produced water in some parts of Alberta (i.e., high concentration of H_2S), requires advanced treatment processes before recycling is feasible. Additionally, produced water storage requires specialized infrastructure, which entails significant capital investment if not already available. In contrast, disposal costs remain comparatively low, and producers benefit from generally accessible deep-well injection sites.

Interviewees also identified the risk associated with the conveyance and storage of produced water. As recycling operations scale up, the potential likelihood and consequence of spills increases, presenting risks that producers are generally unwilling to take. Interviewees expressed concerns not only with the environmental impacts of produced water spills, but also the potential social, reputational, and economic impacts.

Another identified constraint to produced water recycling is the regulatory environment governing HF operations in Alberta. Directive 055 (D055), which defines requirements for produced water storage, was noted by interviewees as imposing limitations on both the allowable on-site produced water storage volume and the maximum duration of storage. As a result, producers commonly shared that using larger HQNS water reservoirs is more cost effective than smaller produced water storage solutions. Similarly, the restrictions set forth by Directive 058 (D058), which prevents the blending of produced water with HQNS water during storage, were identified as a significant barrier. This is particularly impactful for operators in shale formations where produced water recovery volumes are low; when combined with D055's limitations on storage volume and duration, these directives make it challenging for producers to accumulate the necessary produced water volume for subsequent well completions.

4.1.2.4 Future outlook

To conclude, interviewees were asked to identify potential future drivers and conditions that would enable increased produced water recycling rates. A recurring theme was disposal capacity, with interviewees noting that factors such as induced seismicity, pore space competition, and evolving regulations, could all contribute to reduced disposal capacity, and in turn encourage more produced water recycling. Although disposal constraints were not seen as a current operational issue for the interviewees, they acknowledged that such limitations are more likely to happen in the future and a likely response would be operational adjustments favouring produced water recycling. Furthermore, some interviewees hypothesized that producers' economic models for evaluating water sourcing options may not fully account for the complete water lifecycle costs in HF operations, or for the cost of losing access to either HQNS water sources or disposal (e.g., via production curtailment or other emergency measures such as longer distance trucking to alternative disposal locations). This gap can make it difficult to develop a compelling internal business for produced water recycling compared to current water management practices (i.e., HQNS water sourcing and produced water disposal).

Another identified driver for increased produced water recycling was the potential for regulatory amendments that would grant producers greater autonomy over their produced water. For example, adjustments to the storage capacity, duration of storage, and blending during storage were cited as examples of measures that could enhance recycling rates. Several producers indicated active collaboration with the AER to communicate their concerns with the current applicable directives.

5. Jurisdictional Comparison Framework

Section 5.0 defines the framework for comparing the produced water management practices and regulatory frameworks across five key jurisdictions. The comparison framework examines the entire water lifecycle, from water sourcing to produced water recycling or disposal (Figure 1), identifying both commonalities and jurisdiction- and formation-specific challenges. These comparisons, detailed in Section 6, illustrate how operational realities, environmental constraints, and regulatory frameworks collectively influence regional strategies for HF water management.

Figure 4 expands on the typical water lifecycle in HF operations presented in Figure 1. The identifiers (i.e., ID #) within each phase, referenced in Table 3, provide a structured basis for a combined qualitative (i.e., matrix-based) and quantitative (i.e., radar chart) comparison methodology. Additionally, certain phases are designated as producer-specific, as producers are the final decision-makers for the end use of produced water flowing through their process.

A conceptual regulator valve is positioned in Figure 4 prior to produced water disposal, symbolizing a control mechanism influenced by multiple factors and external pressures that modulate water flow through the entire lifecycle. While the overall lifecycle phases remain consistent across jurisdictions, the relative volume of water flowing through each phase varies significantly, influenced by constraints acting on the conceptual regulator valve (Figure 4, ID #4).

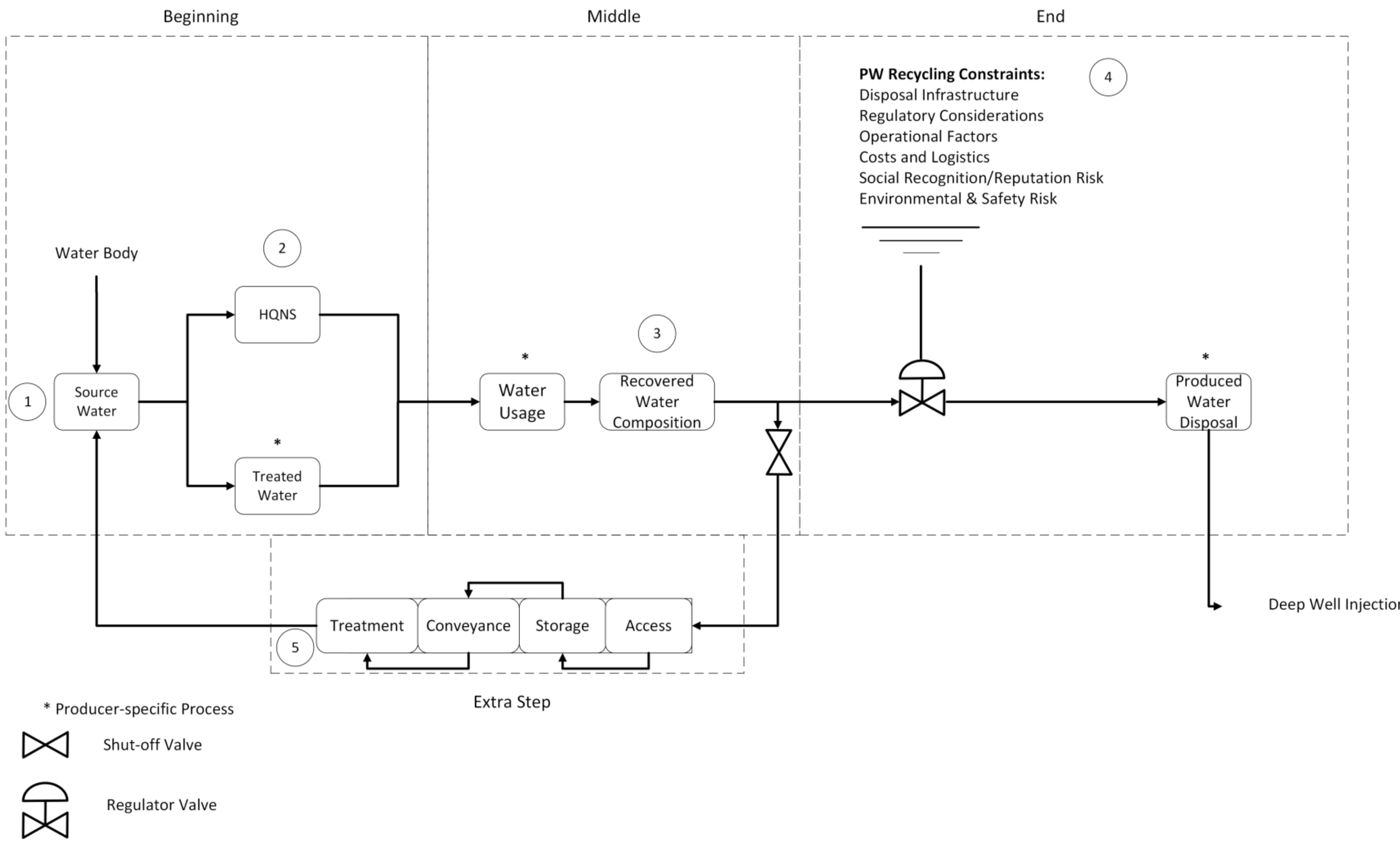


Figure 4. Water lifecycle for typical HF operations. The process includes sourcing to disposal, along with additional stages for produced water recycling (from access to treatment).

Table 3. Comparison description for water lifecycle management approaches in each jurisdiction.

Process Stage	ID #	Approach Used	Evaluation Type
Beginning	1	HQNS water policy stewardship: Jurisdiction comparison matrix Results in Section 6.1	Qualitative
	2	HQNS water sourcing limitations: Radar chart comparison Results in Section 6.2, 6.3, and 6.4	Quantitative
Middle	3	Produced water composition: Radar chart comparison Results Sections 6.2, 6.3, and 6.4	Quantitative
End	4	Produced water recycling constraints: Jurisdiction comparison matrix Results in Section 6.5	Qualitative
Extra Step	5	Produced water treatment considerations: Jurisdiction comparison matrix Results in Section 6.6	Qualitative

For example, ID #1 corresponds to the beginning of the water lifecycle and supports a matrix-style qualitative comparison of HNQS water stewardship across the five jurisdictions.

5.1 Matrix comparison – Qualitative evaluation

Results for ID #1, 4, and 5 are compared qualitatively using a matrix approach across the five jurisdictions (Sections 6.1, 6.5, and 6.6), with the purpose of identifying differences and similarities for further analysis and discussion. The list below provides a high-level overview of the factors used as the basis for qualitative comparison in this study. Additional detail is available in Appendix C:

- **HQNS water policy stewardship:** The regulatory and operational structures that govern the sourcing, prioritization, and management of HQNS water in HF operations (Section 6.1).
- **Produced water recycling constraints:** The factors that influence how produced water is managed after recovery (Section 6.5).
- **Produced water management:** The additional stages in Figure 4 aimed at facilitating produced water recycling (Section 6.6).

5.2 Radar chart – Quantitative evaluation

Results for ID #2 and 3 in Figure 4 are presented using radar chart diagrams to compare each jurisdiction to Alberta (Sections 6.2, 6.3, and 6.4). The approach provides a conceptual framework to emphasize distinctions and similarities between jurisdictions.

As illustrated in Figure 5, each radar chart depicts the relative ranking of four key characteristics which influence the extent of produced water recycling in each jurisdiction: total dissolved solids (TDS), H_2S, Water-Oil Ratio, and HQNS Water Sourcing Limitations. These characteristics were selected because of their significant impact on produced water recycling rates.

The relative ranking is on a scale from 1 to 4, as defined in Table 4. For instance, a value of 4 for TDS indicates a concentration under 4,000 mg/L in produced water, which falls under the AER's range for nonsaline water [18]. Academic literature, applicable regulations, and anonymized and aggregated data provided by interviewees informed the scoring parameters [18, 19]. A larger area in the radar chart indicates a higher potential for produced water recycling.

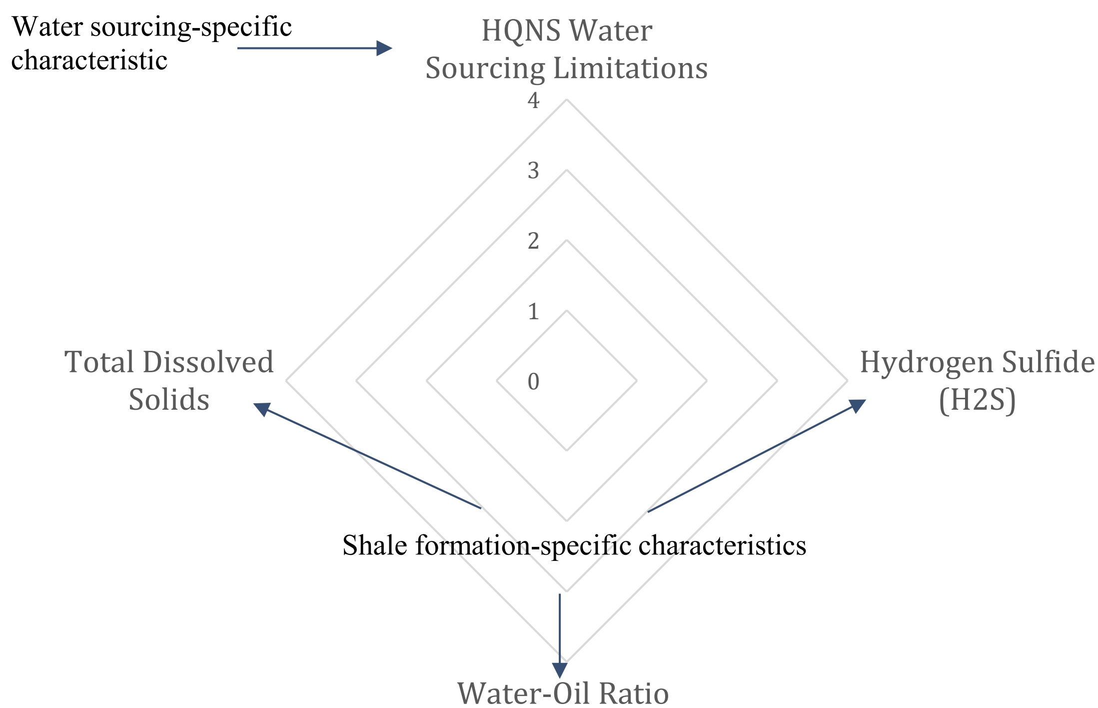


Figure 5. Radar chart for quantitative evaluation.

Table 4. Valuation Table for TDS, H_2S, Water-Oil Ratio, and HQNS water sourcing limitations.

Characteristic	1	2	3	4
Total dissolved solids (TDS) (mg/L)	Very High	High	Moderate	Low
	>150,000	80,000 - <150,000	4,000 - <80,000	<4,000
Hydrogen sulfide (H_2S) (mg/L)	High	Moderate	Low	Negligible / Sweet
	>200	50 - <200	1 - <50	<1
Water-Oil Ratio (bbl - bbl)	Low	Moderate	High	Very high
	0.1 - <1	1 - <2	2 - <4	>4
HQNS water sourcing limitations	Very low risk	Moderate risk	High risk	Very high risk

6. In-depth Jurisdictional Comparison

This section presents the jurisdictional comparisons completed using the methodology in Section 5.0. Per Table 3, results for ID # 1, 4, and 5 from Figure 4 are compared using the qualitative matrix comparison approach introduced in Section 5.1, while results for ID #2 and 3 are compared using the quantitative radar chart approach described in Section 5.2. Through an integrated approach combining qualitative and quantitative assessments, this section supports the identification of actionable insights and lessons to support future improvements in Alberta's produced water recycling landscape (Sections 7.0 and 8.0).

As stated, the quantitative comparison method employs radar charts to visualize data by formation, enabling comparisons between U.S. jurisdictions and the Alberta Montney and Duvernay formations. The unit ranges shown for each formation represent formation-wide averages; however, produced water and shale formation characteristics can vary significantly at the individual well level. Producers located within these formations may observe conditions that differ from the reported values. Note that the radar charts for all formations display the upper range of each comparison dimension.

6.1 ID #1 Comparison. HQNS water stewardship.

Factor	Pennsylvania (Marcellus)	New Mexico (Permian)	Texas (Permian)	Colorado (Niobrara)	Alberta (Duvernay and Montney)
Policy framework	No formal statewide HQNS stewardship policy. 25 PA. Code, Chapter 78a establishes the foundation for regulating unconventional wells as it relates to surface activities (e.g., waste storage and impoundments, spill prevention, and pipelines) [20]. 5 PA.C.S. Act 13 of 2012 and the Clean Streams Law also contain relevant standards for protection of water supplies and wastewater fluids [21, 22].	No formal HQNS water stewardship policy. The Produced Water Act (2019) clarifies permitting for produced water transport and recycling [23]. Goal of New Mexico's Environment Department is to reduce reliance on limited freshwater [24].	Fragmented regulatory oversight across groundwater districts. No unified statewide mandate for water reduction; reliance on market forces. Induced seismicity constraints on disposal are a key driver for recycling [9].	First U.S. statewide mandatory recycling targets adopted under HB 23-1242 and enforced by the Colorado Energy and Carbon Management Commission [12].	The WCP recommends reduced reliance on HQNS water and use of alternative sources (e.g., produced water) [1]. Risk-based assessment is required for sourcing HQNS water [25].
Preference hierarchy	Market/constraint-driven hierarchy due to limited disposal capacity: 1. Produced water recycling. 2. Surface water/groundwater [26].	Policy-influenced hierarchy: 1. Produced water recycling (encouraged by the Produced Water Act). 2. Brackish water. 3. HQNS water [27, 24].	Market/constraint-driven hierarchy due to disposal limitations and high produced water recovery volumes: 1. Produced water recycling [28]. 2. Freshwater/brackish water (for make-up and blending) [29].	Policy-mandated hierarchy: 1. Produced water recycling or alternatives to HQNS water. 2. HQNS water [12].	Policy-influenced hierarchy: 1. Saline groundwater and produced water recycling. 2. Alternative non-saline water. 3. HQNS Water [1].
Operational reality	Produced water recycling is widely adopted as disposal options are limited. HQNS water sourcing considers pass-by flow requirements for environmental protection [26].	Structural water scarcity due to arid climate [30]. The Produced Water Act facilitates internal recycling but limits external/surface water discharge [24]. Logistics and treatment infrastructure remain key barriers [31, 32].	Produced water is abundant in the Permian Basin [28]. Produced water recycling is rapidly expanding as a means to handle large produced water volumes and due to induced seismicity [8], though logistics and pipeline density remain key operational challenges [29].	Colorado is experiencing increasingly severe droughts, leading every industry sector to explore new conservation measures [33]. Infrastructure for produced water treatment and conveyance is still developing [11].	Policy encourages the use of alternatives to HQNS water, but HQNS water is still widely available and widely used. Produced water recycling adoption is slower due to various factors, per WaterSMART's 2024 report [2].
Incentives	No structured incentives. Produced water recycling is the most viable water management option due to limited deep-well disposal capacity [34, 35].	Regulatory certainty and conservation: The Produced Water Act clarifies liability and grants regulatory certainty for transport and recycling.	Few formal incentives. Cost avoidance and operational stability: Avoiding trucking costs and Railroad Commission-enforced seismicity shutdown costs [8]. Pilot programs are encouraged to develop beneficial recycling technology [36].	New rules in Colorado (i.e., HB23-1242) aim for a minimum of 4% (produced water recycle or alternatives) by 2030, rising to 35% by 2038. HB23-1242 provides compliance flexibility through credit trading [11]. Failure to comply with the new rules will impact future approvals for new wells [37].	Alternative water sourcing can be exempt from applying for a new *Water Act* licence [2]. Under some circumstances, projects that have demonstrated significant progress towards meeting Water for Life conservation goals (i.e., water use performance and water management initiatives) in the previous licence term may apply for licence renewal based on a simplified evaluation [1].
Barriers	High salinity (i.e., TDS): High salinity in produced water increases the cost of advanced treatment required for oilfield and non-oilfield recycling [38].	Water quality: Limits on the external use of produced water due to the presence of metals, organics, and naturally occurring radioactive materials, thus restricting surface discharge unless it meets treated produced water standards in Subsection D of 20.6.8.400 NM Administrative Code [39].	Induced seismicity: Regulator-imposed volume restrictions and suspensions on deep disposal wells [8, 40]. High salinity and large volumes challenge treatment infrastructure scale-up [10].	High initial capital investment is required to build centralized treatment and conveyance infrastructure to meet the new rules [33].	The presence of H_2S in some produced water increases the cost and complexity of treatment [2]. High initial capital investment would be required to build centralized treatment and conveyance infrastructure.

6.2 ID #2 and 3 comparison. Marcellus Formation. PA and AB.

Why it matters:
Both jurisdictions face high levels of TDS in PW, increasing treatment complexity and raising operational and economic costs.

Pennsylvania

Very high TDS: 100,000 - 250,000 mg/L in the Marcellus Shale [116].

Alberta

Very high TDS: 100,000 - 280,000 in the Duvernay and 200,000 – 280,000 mg/L in the Montney [117].

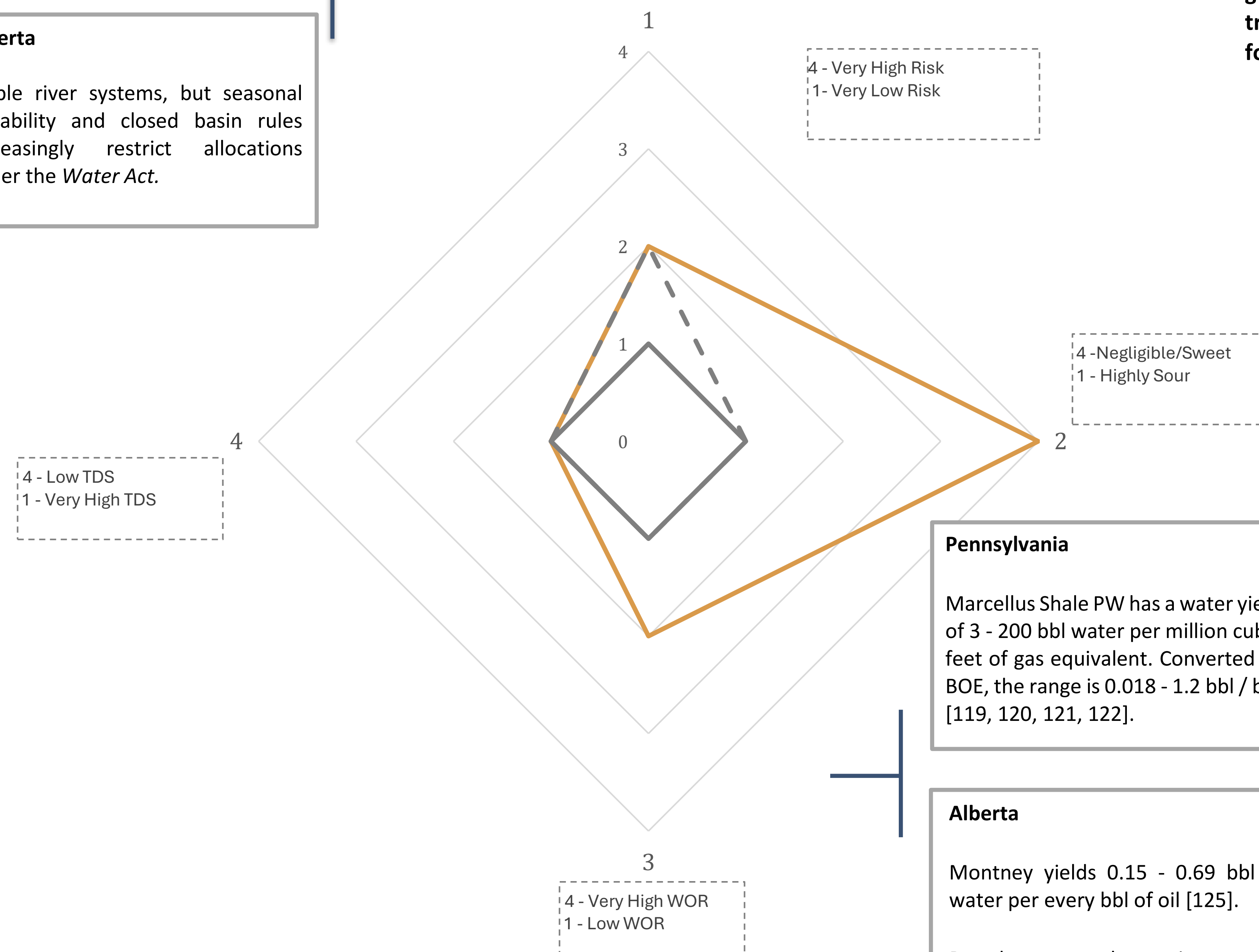
Pennsylvania

Physical availability of water is relatively high, but regulations limit withdrawals and discharges in sensitive water bodies.

Alberta

Stable river systems, but seasonal variability and closed basin rules increasingly restrict allocations under the *Water Act.*

Why it matters:
HQNS water sourcing limitations differ significantly. Pennsylvania's Marcellus and the Alberta Montney (Northwest Alberta) generally face low overall water availability challenges. Despite Pennsylvania's overall high HQNS water availability, the state has designated a series of sensitive stream reaches where limits on withdrawals and discharges apply, increasing its water sourcing limitations compared to the Montney. The east Duvernay of Central Alberta also faces more water sourcing limitations compared to the Montney.



Why it matters:
In Alberta, high H_2S concentrations can increase treatment complexity and safety concerns, raising costs. In contrast, the Marcellus Shale is generally a sweet play, simplifying water treatment by eliminating the widespread need for specialized sour water management.

Pennsylvania

While there are no direct measurements of H_2S in Marcellus produced water, neighbouring shale formations have negligible sulfate concentrations, thus minimizing sulfur-reducing bacteria activity [114].

Alberta

Potential for high sourness in the Duvernay and the Montney, >2,000 mg/L [96].

Pennsylvania

Marcellus Shale PW has a water yield of 3 - 200 bbl water per million cubic feet of gas equivalent. Converted to BOE, the range is 0.018 - 1.2 bbl / bbl [119, 120, 121, 122].

Alberta

Montney yields 0.15 - 0.69 bbl of water per every bbl of oil [125].

Based on producer input, the Duvernay has a lower water-oil ratio than the Montney, though it is challenging to quantify.

Why it matters:
Both jurisdictions have relatively low water-oil ratios, which presents a barrier to produced water recycling.

Pennsylvania, Marcellus
Alberta, Montney
Alberta, Duvernay

6.3 ID #2 and 3 comparison. Permian Basin. NM, TX, and AB.

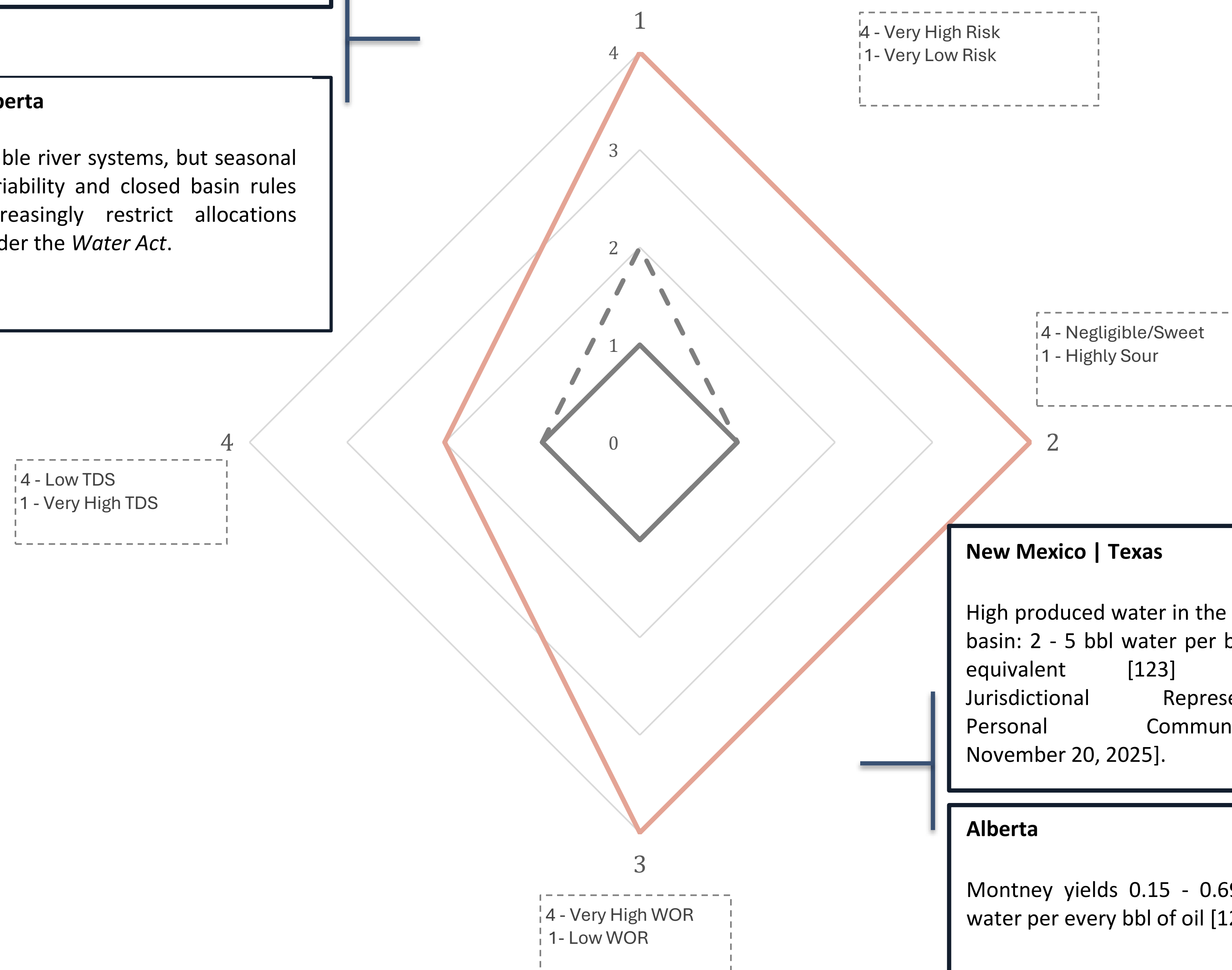
New Mexico | Texas

Regions with chronic drought risk, high agricultural competition, and documented restrictions on water withdrawals.

Alberta

Stable river systems, but seasonal variability and closed basin rules increasingly restrict allocations under the *Water Act*.

Why it matters:
In New Mexico and Texas, persistent structural water scarcity associated with its more arid climatic conditions makes long-term conservation an essential operational requirement.



Why it matters:
In Alberta, high H_2S concentrations can increase treatment complexity and safety concerns, raising costs. In contrast, the Permian is generally a sweet play, simplifying water treatment by eliminating the widespread need for specialized sour water management.

New Mexico | Texas

While 85% of natural gas in the Permian shows H_2S concentration >100 mg/L, partitioning in PW is low to negligible [113].

Alberta

Potential for high sourness in the Duvernay and the Montney, >2,000 mg/L [96].

Why it matters:
Both jurisdictions face high levels of TDS in PW, increasing treatment complexity costs.

New Mexico | Texas

High TDS: 120,000 - 140,000 mg/L in the Permian Basin [99].

Alberta

Very high TDS: 100,000 - 280,000 in the Duvernay and 200,000 – 280,000 mg/L in the Montney [117].

New Mexico | Texas

High produced water in the Permian basin: 2 - 5 bbl water per bbl of oil equivalent [123] [TX/NM Jurisdictional Representative, Personal Communications, November 20, 2025].

Alberta

Montney yields 0.15 - 0.69 bbl of water per every bbl of oil [125].

Based on producer input, the Duvernay has a lower water-oil ratio than the Montney, though it is challenging to quantify.

Why it matters:
The Permian Basin returns relatively high volumes of PW compared to Alberta's formations. The additional PW volumes reduce per-unit costs of storage and treatment trains and can justify capital expenditures for produced water management infrastructure, particularly in the context of disposal constraints.

Permian Basin
Alberta, Montney
Alberta, Duvernay

6.4 ID #2 and 3 comparison. Niobrara Formation. CO and AB.

Why it matters:

High water stress in Colorado and mandatory recycling targets (i.e., 4% to 35%) enforce reduced HQNS utilization.

Colorado

Semi-arid states with tight water allocation frameworks.

Alberta

Stable river systems, but seasonal variability and closed basin rules increasingly restrict allocations under the *Water Act.*

Why it matters:
In Alberta, high H_2S concentrations can increase treatment complexity and safety concerns, raising costs. In contrast, the Niobrara Formation in Colorado is predominantly a sweet play where negligible H_2S simplifies recycling and treatment, keeping costs comparatively low.

Colorado

While there are no direct measurements of H_2S in Niobrara PW, sulfates in PW range average ~50 mg/L. Sulfate-reducing bacteria activity can produce H_2S [115].

Alberta

Potential for high sourness in the Duvernay and the Montney, >2,000 mg/L [96].

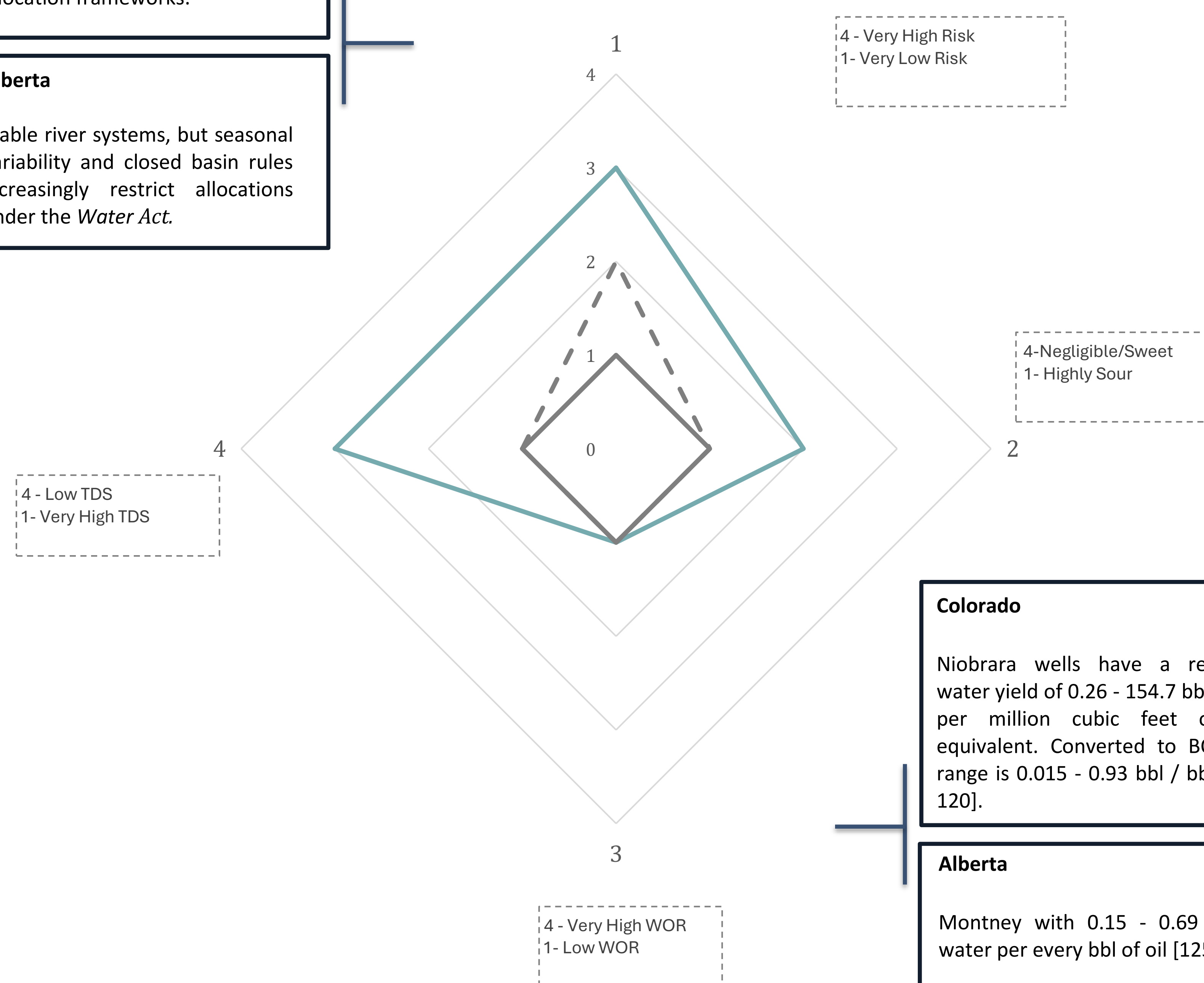
Why it matters:
Lower TDS in PW compared to Alberta enables recycling, as it reduces both treatment requirements and operational complexity.

Colorado

Moderate TDS: 20,000 - 60,00 mg/L in the Niobrara [118].

Alberta

Very high TDS: 100,000 to 280,000 in the Duvernay and 200,000 – 280,000 mg/L in the Montney [117].



Colorado, Niobrara

Alberta, Montney

Alberta, Duvernay

Colorado

Niobrara wells have a reported water yield of 0.26 - 154.7 bbl water per million cubic feet of gas equivalent. Converted to BOE the range is 0.015 - 0.93 bbl / bbl [124, 120].

Alberta

Montney with 0.15 - 0.69 bbl of water per every bbl of oil [125].

Based on producer input, the Duvernay has a lower water-oil ratio than the Montney.

Why it matters:
Availability of PW in the Niobrara Formation is similar to that of formations in Alberta, which presents a barrier to produced water recycling.

6.5 ID #4 comparison. Produced water recycling constraints.

Factor	Pennsylvania (Marcellus)	New Mexico (Permian)	Texas (Permian)	Colorado (Niobrara)	Alberta (Duvernay and Montney)
Disposal infrastructure	Limited disposal capacity exists statewide, with only a small number of Class II injection wells (i.e., for fluids associated with oil and natural gas production). As a result, industry is compelled to pursue recycling as a practical necessity [41].	Disposal primarily relies on Saltwater Disposal Wells (SWD) regulated under the Underground Injection Control (UIC) program [42]. Existing SWD wells face increasing scrutiny due to seismicity concerns and environmental risks [43].	Although the Permian Basin region in Texas maintains one of the largest inventories of SWD wells in the United States, a substantial number of these wells are currently subject to suspensions issued by the Railroad Commission in response to induced-seismicity concerns [9].	Colorado maintains less Class II disposal well capacity than Texas and New Mexico [44]. New requirements prohibit the construction of new produced water storage and treatment facilities in any “disproportionally impacted community” under HB 23-1242 [45].	Alberta has substantial deep-well injection capacity, supported by a large inventory of disposal wells, which generally allows subsurface disposal to remain a viable and cost-competitive alternative to produced water recycling [2].
Disposal regulatory considerations	Class II injection well control program is administered at the federal level leading to a longer approval process for new injection wells compared to neighbouring Ohio and West Virginia. In addition to a federal permit, Class II disposal wells in Pennsylvania require a separate permit from the Pennsylvania Department of Environmental Protection [46, 47, 48].	The backlog of permit applications for Class II disposal wells, sometimes taking six to nine months or longer to process, acts as an operational limit on new capacity creation [49]. The New Mexico Oil Conservation Division (OCD) has significantly increased its focus on induced seismicity management in the Permian Basin [50].	Disposal is regulated by the Railroad Commission of Texas under Statewide Rules 8, 9, and 46 [8]. Seismicity concerns have led to tighter permitting and operational restrictions on new wells and injection volumes. House Bill 49 (2025) introduced liability protections for recycling and discharge of treated produced water, encouraging recycling [51].	Produced water is typically disposed of through Class II injection wells, which are regulated by the Colorado Oil and Gas Conservation Commission (COGCC) and must comply with all state and federal requirements regarding well construction, casing, protection of groundwater, injection pressures, volume limits, and seismicity risk. Per the Oil and Gas Development Policy No. 500-001, disposed fluids are subject to a royalty rate per barrel [52].	Governed by AER directives (i.e., D051 - Injection and Disposal Wells). D051 provides requirements for the design, integrity logging, monitoring, and testing of injection and disposal wells to ensure safe disposal of fluids, proper wellbore isolation, and protection of groundwater and subsurface formations [53].
Operational impact	Producers in Pennsylvania cannot rely on deep-well injection due to the limited capacity of in-state disposal wells and the high cost of out-of-state disposal in Ohio [34, 48].	In New Mexico, operational strategy is heavily dictated by an arid climate, which amplifies water scarcity and makes produced water recycling more enticing for HF operations [54]. Investments in pipeline infrastructure are enabling a different approach to water management, slowly displacing long-haul trucking. Logistical gaps remain a major cost driver for remote operations [55].	Texas has historically relied on disposal well infrastructure. Due to the high volumes of produced water, now exceeding 22 million barrels per day in the Permian Basin, disposal capacity is being strained. A surge in seismic events has led to implementation of strict Seismic Response Areas (SRAs) and suspended deep-well disposal permits. Produced water recycling is seen as critical to ensure reliable production [56, 57, 58].	Operational planning in Colorado is shaped by persistent water-scarcity conditions and by the priorities outlined in the state’s 2023–2025 Water Plan, which emphasizes a demand balance between municipal, watershed, agriculture, and industrial water uses [59]. The Colorado Produced Water Consortium convenes individuals with expertise in produced water to reduce the use of HQNS water and increase the recycling of produced water in oil and gas operations [60]. Colorado’s phased produced water and alternative sources recycling targets are expected to decrease HQNS water dependence [12].	Deep-well disposal remains the primary destination for produced water [2]. The HF sector continues to rely on Alberta’s deep-well disposal capacity due to the high cost of treatment and the convenience of existing infrastructure.

Factor	Pennsylvania (Marcellus)	New Mexico (Permian)	Texas (Permian)	Colorado (Niobrara)	Alberta (Duvernay and Montney)
Costs and logistics	Observed costs are not uniform. Costs fluctuate both between shale formations and between producers. All-in disposal cost, including trucking from PA to Ohio in the Marcellus range between $10 – $12 USD/bbl. [61]. On-site recycling costs are estimated between $1.20 – $10.00 USD/bbl. (Depending on if filtration or reverse osmosis is required) [62].	Observed costs are not uniform. Costs fluctuate both between shale formations and between producers. Historic benchmark disposal cost: $0.60 - $0.70 USD/bbl. [56]. Transport via pipeline or trucking can add between $0.3 and $2.50 USD/bbl. [63]. Note that a regulatory fee was proposed at $0.05/ bbl. (Senate Bill 178, 2025) for produced water, with exceptions for use in EOR, recycling, and other regulated uses. The Bill was postponed indefinitely on February 17, 2025 [64]. On-site recycling costs range between $0.75 – 1.50 USD/bbl. for HF [56].	Observed costs are not uniform. Costs fluctuate both between shale formations and between producers. Historic benchmark disposal cost: $0.60 - $0.70 USD/bbl. [56]. Transport via pipeline or trucking can add between $0.3 and $2.50 USD/bbl. [63]. On-site recycling costs range between $0.75 – 1.50 USD/bbl. for HF [56].	Observed costs are not uniform. Costs fluctuate both between shale formations and between producers. All-in disposal cost (2007): $0.4 - $3.95 USD/bbl. [65]. On-site recycling costs are not widely reported.	Observed costs are not uniform. Costs fluctuate both between shale formations and between producers. All-in disposal cost, based on market data is between $1.00 - $10.00 CAD [66].
Environment, safety, and reputation	Media attention on naturally occurring radioactive material in municipal landfills and on the practice of brine road-spreading has contributed to heightened public concern around the sector's environmental profile [67]. Growing public opposition to gas-fired data centers has increasingly drawn connections between the technology sector and upstream natural-gas production, including HF [68].	Some advocacy groups in New Mexico have referred to produced water recycling in a negative light, which has introduced public-perception challenges for operators [69].	Residents in the Permian Basin are reporting structural cracks in buildings due to induced seismicity events, presenting a public perception barrier to continued use of disposal infrastructure [70].	Colorado's produced water recycling requirements ensure that operator performance is documented through publicly accessible rulemaking and reporting processes. To prevent reputational backlash based on produced water recycling performance, operators are expected to make capital investments in recycling infrastructure.	Most HF operators in Alberta consider that the risk and potential liability of transporting and storing produced water is high, limiting adoption of recycling practices.
Beneficial Reuse	Use Case – Status Well Completion – **Allowed** Inter-Operator Transfer – **Allowed** Industrial Cooling/Processing – **Allowed** Irrigation/ Agriculture – **Prohibited** Discharge to Environment – **Prohibited**	Use Case – Status Well Completion – **Allowed** Enhanced Oil Recovery (EOR) – **Allowed** Industrial Cooling/Processing – **Pilot Stage Only** Irrigation / Agriculture – **Prohibited** Discharge to Environment – **Prohibited**	Use Case – Status Well Completion – **Allowed** Enhanced Oil Recovery (EOR) – **Allowed** Industrial Cooling/Processing – **Allowed** Irrigation / Agriculture – **Pilot Stage Only** Discharge to Environment – **Adopting Rules and Parameters for Discharge**	Use Case – Status Well Completion – **Quota** Enhanced Oil Recovery (EOR) – **Allowed** Industrial Cooling/Processing – **Allowed** Irrigation / Agriculture – **Prohibited** Discharge to Environment – **Prohibited**	Use Case – Status Well Completion – **Allowed** Enhanced Oil Recovery (EOR) – **Allowed** Industrial Cooling/Processing – **Prohibited** Irrigation / Agriculture – **Prohibited** Discharge to Environment – **Prohibited**

6.6 ID #5 comparison. Produced water management.

Factor	Pennsylvania (Marcellus)	New Mexico (Permian)	Texas (Permian)	Colorado (Niobrara)	Alberta (Duvernay & Montney)
Access	Despite relatively low produced water volumes, producers in the Marcellus have created a centralized wastewater economy, using permanent treatment and recycling hubs [35].	New Mexico generates nearly 2,100 million bbl/year of produced water [71]. Rule 19.15.34 mandates that operators prioritize produced water recycling and report the ratio of HQNS to recycled water for every well completion [23].	Produced water recovery in the Texas Permian Basin ranges between two and five bbl/bbl. About 50–80% of produced water is recycled internally for HF in the Permian [72].	Effective January 1, 2026, House Bill 23-1242 mandates a 4% recycling floor for all new development plans by 2030, scaling to 35% by 2038 to combat systemic drought [12].	Low water oil ratios and long distances between well pads means large-scale produced water storage would be required to accumulate sufficient volumes for significant recycling [2].
Storage	Produced water storage using temporary pits is prohibited by the DEP Title 25 Chapter 78a. Unless a permit has been obtained under DEP Title 25 Chapter 78a.60, operators collect their produced water in a tank or series of tanks. Secondary containment (which must hold the largest tank + 10% for precipitation) is required for all new, refurbished, or replaced aboveground primary containment [20, 46]. In Pennsylvania, general permit WMGR123 allows oil and gas liquid waste to be used for development or hydraulic fracturing. The regulation states that storing waste for more than one year is considered disposal, unless there is clear and convincing evidence proving otherwise [73].	New Mexico Environment Department mandates that any produced water stored outside the oilfield must be handled in a completely closed-loop system to prevent any direct or indirect discharge to ground or surface water [74]. All primary liners shall be 30-mil (1 mil = 1/1000 in) flexible PVC, 45-mil linear low-density polyethylene (LLDPE) string reinforced or 60-mil high density polyethylene (HDPE) liners. Secondary liners shall be 30-mil LLDPE string reinforced or equivalent with a hydraulic conductivity no greater than 10^{-9} cm/sec LLDPE liners are required for all recycling containments and must include a leak detection system between liners with a unique identifier number [75]. Permanent pits can be used for collection, retention or storage of produced water for the duration provided in its permit [76].	Regulatory requirements under Texas Railroad Commission Statewide Rules 8, 9, and 46 mandate secondary containment, leak detection, and integrity testing for storage facilities [77, 78]. Producers shall file financial security (i.e., performance bond or letter of credit/cash deposit) based on the total pit capacity. A produced water recycling pit shall ensure storage capacity to maintain two feet of freeboard plus the capacity to contain the volume of precipitation from a 25-year, 24-hour rainfall event. Produced water recycling pits shall be lined: natural liners can be used for up to 1 year, and synthetic liners for longer [78]. Texas establishes a regulatory limit on the duration that produced water may remain in storage following the cessation of drilling operations; however, no specific time limit is prescribed for produced water while it remains in active, operational storage [79, 78].	Storage pits are allowed for produced water storage. All containment structures must include a primary and secondary liner system (synthetic, geosynthetic or compacted foundation). with an automated leak-detection layer. Produced water storage or treatment facilities are included in the definition of Centralized E&P Waste Management Facilities [80]. Per ECMC Rule 909, producers may operate multi-well pits for a maximum period of three years, unless a permit is obtained to operate the pit under Rule 907 as a Centralized E&P Waste Management Facility, or the pit has been granted grandfathered status in Huerfano, Las Animas, Logan, Morgan, Washington, or Yuma Counties, however, the rule is not specific for single-well pits [81].	D055 sets the minimum requirements for storage of all materials generated by upstream oil and gas operations, including produced water. D055 indicates that produced water shall be stored in Engineered Containment Ponds (ECPs) and aboveground synthetically lined walled storage systems (AWSSs) with secondary containment measures, although fixed limits are placed on the total volume stored on-site and the allowed duration of storage. Furthermore, liners in D055 have both a minimum thickness and a prescriptive hydraulic conductivity limit [82]. Facilities with continuous sulphur emissions, such as produced water tanks, must submit a breakdown of all sources to the AER [83].
Conveyance	DEP Title 25 Chapter 78 mandates that pipelines transporting produced water must be installed aboveground unless crossing roads or waterways [20]. Large operators are now building inter-connected pipeline networks that allow them to shuttle water across counties to wherever the active fracturing activity is located, reducing their reliance on expensive out-of-state trucking [84].	State involvement is generally limited to research pilots supported by organizations like the New Mexico Produced Water Research Consortium, with no direct subsidies. Produced water recycling efforts have supported the consolidation of midstream services for pipeline conveyance. 12-inch lay flat hose is used for last-mile logistics. As more conveyance is done through pipelines, it is expected to become more common than trucking [85, 86].	State involvement is generally limited to research pilots supported by organizations like the Texas Produced Water Consortium, with no direct subsidies. Although no direct state incentives exist for midstream water companies, they may benefit indirectly from programs such as the Texas Water Fund that finance desalination and produced water treatment projects [87]. Midstream water companies are investing in regional pipeline systems to reduce reliance on trucking and improve cost efficiency [56].	To meet the state's recycling mandate, operators will have to build new conveyance infrastructure, likely using permanent trunklines for regional disposal and temporary lay-flat pipelines for local completions [88].	Increased site traffic for trucking, capital cost of new pipeline infrastructure, risk and liability concerns of potential spills, and long-distance conveyance are noted as considerations by AB operators. Producers in AB have historically not built complex networks for PW conveyance, as they would be duplicative of HQNS water lines [2]. In 2025, AER's D077 enabled temporary surface pipelines to move produced water (defined as higher risk water group 3) between sites, providing more flexibility for recycling. The impact of this directive amendment has yet to be fully assessed [89].

Factor	Pennsylvania (Marcellus)	New Mexico (Permian)	Texas (Permian)	Colorado (Niobrara)	Alberta (Duvernay & Montney)
Treatment	HQNS water or low-TDS recycled water is typically blended with produced water to reach a target salinity. Chemical precipitation is used for high ion concentrations (e.g., Barium and Strontium) [90].	Chemical oxidation targeted at removing recalcitrant organics, stripping for Volatile Organic Compounds (VOCs), and advanced membrane filtration are considered for produced water treatment [91, 92]. New Mexico's Water Quality Control Commission is moving closer to finalizing regulations to encourage pilot projects for treatment and recycling of produced water through 2030 [93].	Current research focuses on the purification of produced water to generate clean brine for in-situ recycling and to reduce demand on freshwater resources [94]. Sour water treatment is typically achieved through ClO_2 oxidation [95].	Treatment is required prior to placement of produced water in a production pit [80].	Alberta producers cite high capital and operating costs for on-site and off-site treatment, with a particular emphasis on H_2S content [2].

7. Potential Approaches to Address Produced Water Recycling Challenges

The shale formations studied in Pennsylvania, New Mexico, Texas, and Colorado have unique physical characteristics, regulatory requirements, and operational realities which both enable and motivate a higher rate of produced water recycling than occurs in Alberta. In Alberta, most shale formations generally yield low volumes of recoverable produced water, limiting the availability of fluid for on-site recycling. Where produced water is available, it frequently exhibits high salinity and H_2S concentrations, increasing produced water treatment complexity and costs relative to the U.S. shale formations examined. Currently, most producers in Alberta also benefit from available deep-well disposal capacity, which, in conjunction with access to HQNS water for their operations and regulatory requirements for produced water storage, reduces the driver to pursue more produced water recycling.

Section 7 highlights how different jurisdictions address the above challenges and explores the configurations that are consistently associated with higher rates of produced water recycling. Figure 6 provides a supporting framework for this section by showing the critical decision points and potential barriers that can arise throughout the main phases of produced water recycling (i.e., access, storage, conveyance, and treatment illustrated highlighted in blue).

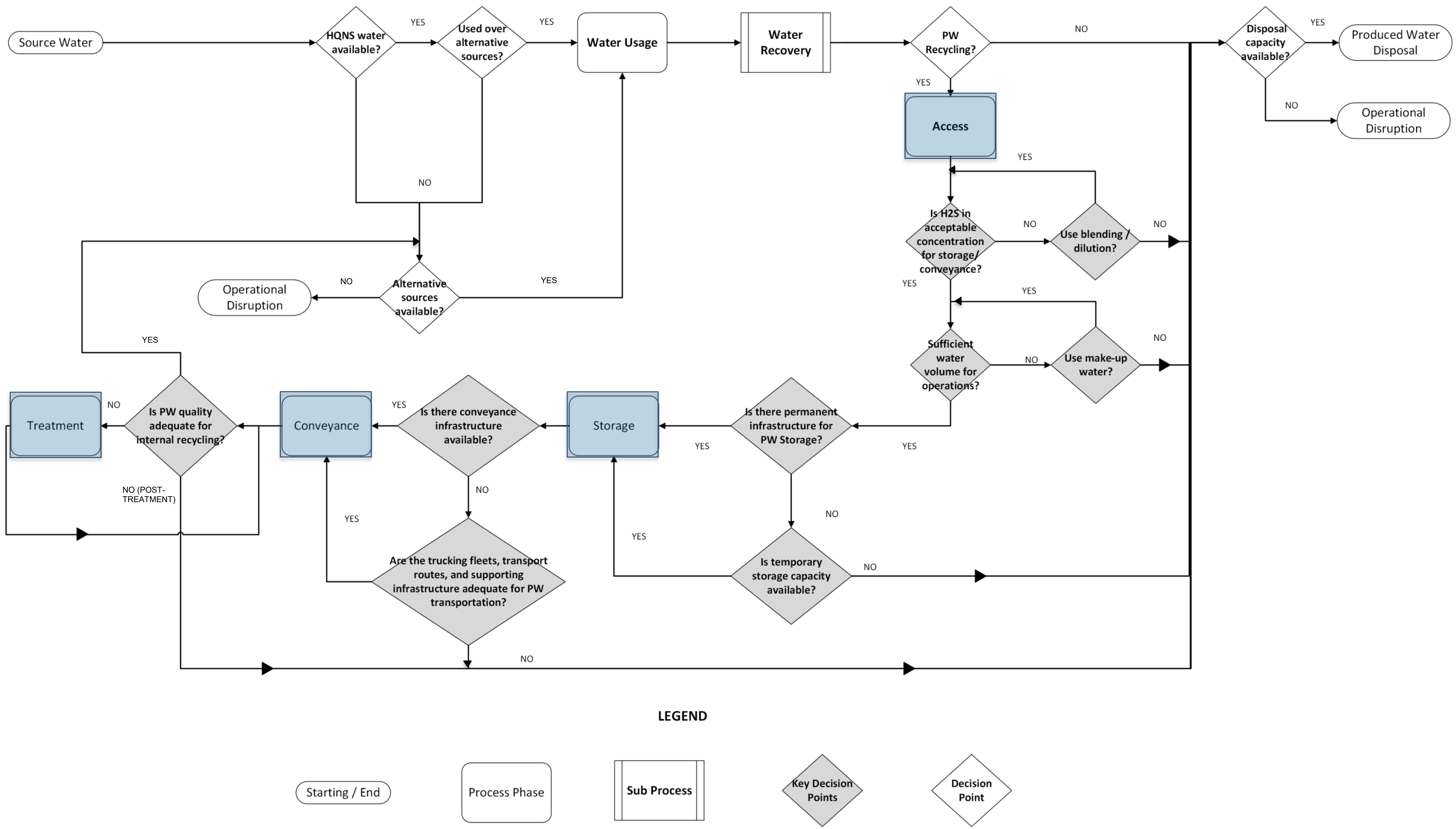


Figure 6. Produced water management lifecycle and producer decision points.

7.1 Access phase

During the access phase in Figure 6, high levels of H_2S and low produced water recovery volumes were identified as the main decision-making points for producers.

7.1.1 High Levels of H_2S

H_2S concentrations in produced water from the Montney and the Duvernay formations can exceed 2,000 mg/L [96], which is higher than levels typically found in the studied U.S. formations. When encountering this decision point in Figure 6, many Alberta operators opt to send sour produced water straight to disposal. Where sourness is encountered in the U.S., common management approaches during the access phase include blending with HQNS water or alternative sources and implementing measures to prevent sulfate reduction to H_2S during storage and conveyance. Further details on H_2S treatment practices are provided in Section 7.4.

7.1.2 Low produced water recovery volumes

In states such as Colorado, Texas, and New Mexico, producers aggregate produced water through centralized storage and treatment hubs. These hubs enable producers to pool larger volumes produced water, build inventory, and schedule recycling when needed. The approach is particularly valuable in the Colorado Niobrara Formation, where water recovery volumes are lower than in the Permian Basin.

Additionally, blending produced water with HQNS water or alternative sources (e.g., brackish groundwater) sources is common in Pennsylvania and Texas to achieve fit-for-purpose quality for HF operations. In formations with relatively modest recovery volumes compared to the Permian Basin, such as Pennsylvania's Marcellus Formation, limited deep-well disposal capacity acts a further incentive for investment in recycling infrastructure. Moreover, between 2009 and 2010, several producers in the Pennsylvania portion of the Marcellus Formation began trialing produced water filtration and blending for use in new wells, achieving savings from avoided disposal fees, less HQNS water acquisition, and trucking costs [30].

While producers in Alberta do not experience the same recovery rates of produced water seen in the Permian Basin, blending strategies used by producers in the Marcellus Formation and Permian Basin could be considered for deployment. Blending during storage could enhance operational flexibility by supplementing the volumes required for HF operations in the Duvernay and Montney Formations, which have comparatively low produced water yields, while simultaneously lowering TDS and H_2S concentrations ahead of treatment. Currently, Alberta's D058 limits producers' ability to blend produced water with HQNS water and alternative sources while in storage.

7.2 Storage phase

During the storage phase in Figure 6, permanent and temporary storage capacity were identified as the main decision-making points for producers.

7.2.1 Permanent and temporary storage capacity

Produced water storage practices differ significantly between jurisdictions, driven largely by contrasting regulatory regimes:

- In Texas, produced water is typically stored in large, centralized, surface-level impoundments with secondary containment measures (e.g. berms), monitoring, and integrity testing measures. Impoundments are subject to the installation of double liners when infrastructure inspections won't happen annually. Produced water impoundments operating for more than one year must use a synthetic liner meeting minimum mechanical properties (i.e., performance based) such as a breaking strength ≥ 40 lb/in, puncture resistance ≥ 15 lbf, and, where applicable, seam strength ≥ 15 lb/in. If the liner is not drained and inspected at least annually, a double liner with an interstitial leak-detection system is required. In addition, operators must prevent stormwater run-on using perimeter controls (e.g., berms, ditches, and site grading), and interior side slopes may be no steeper than 3H:1V [78].

- In New Mexico, produced water storage is mandated in closed-loop systems to prevent environmental discharge, and double-synthetic liners are required for all produced water containment. Recycling containments are required to have containment in a levee with an inside grade no steeper 2H:1V, and outside grade no steeper than 3H:1V. Other requirements include that primary liners shall have a minimum thickness between 30 and 60 mil, depending on the material. Finally, secondary liners shall be 30 mil LLDPE string reinforced or equivalent with a hydraulic conductivity no greater than 10^{-9} cm/s [75].

- In Colorado, produced water storage typically relies on lined impoundments (double synthetic lined, mixed 1-synthetic liner and compacted soil, or synthetic plus geotextile liner) and Above-Ground Storage Tanks (ASTs). For centralized waste management facilities, synthetic impoundment liners are required to have a minimum thickness of 60 mil, with synthetic or fabricated liner covering the bottom and interior sides of the impoundment. If compacted soil is used as a second layer, the foundation for the liner (with hydraulic conductivity x 10^{-7} cm/s) will be constructed with material containing no sharp rocks, debris, or other material that could puncture the liner. The foundation for the liner shall have a minimum thickness of 24 inches after compaction [97].

- In Pennsylvania, produced water storage is typically contained in ASTs and mobile tanks with secondary containment by dikes. As of October 2016, produced water impoundments are now closed or operate under a permit from the Department of Environmental Protection [98].

The regulatory requirements for produced water storage in Alberta, per D055, feature key differences from other jurisdictions which impact produced water recycling. For example, D055 specifies that stored materials, including alternative water, must be actively used and must not be stored for longer than one year. While some states, such as Pennsylvania, New Mexico, and Colorado do impose conditions on the duration of produced water storage, these limitations are generally more flexible, and can often be waived or extended, especially when compared to the shorter timeframes required in Alberta (as detailed in Section 6.6).

In addition, D055 limits individual AWSS produced water storage capacity to 6,600 m^3 and total on-site storage to 30,000 m^3. During interviews, some producers have previously identified these constraints on AWSS storage as barriers to expanding produced water recycling programs, including large-scale, centralized produced water treatment hubs. Across the U.S. jurisdictions analyzed, regulations do not establish a fixed maximum capacity for either individual produced water storage units or total on-site storage. When an embanked structure reaches the state-specified dimensions, regulators may apply design and oversight thresholds, but no direct storage limits.

Another difference is the use of liners and containment measures for produced water storage. D055 requires ECPs to have both a primary and secondary containment system, with a primary synthetic liner with a minimum thickness of 60 mil and hydraulic conductivity of less than 10^{-7} cm/s and a secondary composite liner (i.e., synthetic liner and either a compacted clay liner or a geosynthetic clay liner). AWSSs planned for use longer than two years require two synthetic liners for primary containment (minimum thickness of 40 mil), a second synthetic liner with a minimum thickness of 30 mil directly beneath, and secondary containment consisting of a dike system with a third synthetic liner.

7.3 Conveyance

During the conveyance phase in Figure 6, permanent and temporary conveyance infrastructure were identified as the main decision-making points for producers.

7.3.1 Permanent and temporary produced water conveyance

Produced water conveyance is governed largely by economics, with volume, distance, and regulatory requirements primarily driving costs. In the Permian Basin, the exceptionally high produced water volumes and regulatory regime support the use of both temporary surface pipelines for water conveyance (TSPW) and permanent regional pipeline networks as an alternative to trucking, which becomes uneconomic at high volumes. These pipeline networks are commonly owned and operated by water midstream companies. Although produced water recovery volumes from the Marcellus and Niobrara Formations are not as high as in the Permian Basin, disposal capacity constraints and a market-driven approach to produced water recycling have also enabled the participation of water midstream companies in these jurisdictions in the development of conveyance and treatment infrastructure.

In contrast, Alberta producers depend more on short-haul trucking to move produced water to disposal, with lower utilization of permanent pipeline infrastructure. Among other factors, the storage limitations noted in Section 7.2 challenge the business case for large, permanent conveyance systems. While AER D077 outlines the testing and operational requirements for TSPW using lay-flat hose, the interviewed producers generally consider the potential liability of risks and spills while using temporary conveyance to offset any potential benefits.

7.4 Treatment

During the treatment phase in Figure 6, produced water quality was identified as the main decision point for producers. Produced water treatment strategies are primarily dictated by water quality and the desired end-use, which vary across the formations studied:

- In the Permian Basin, produced water is characterized by high salinity, with TDS often exceeding 120,000 mg/L [99]. Treatment centers on coagulation for residual H_2S removal, friction reducers, and filtration.
    - New Mexico's Environment Department encourages producers to pilot novel treatment methods through the New Mexico Produced Water Research Consortium, and the Water Quality Control Commission is moving closer to finalizing regulations to allow for more treatment and recycling pilots [93, 100]. In Texas, research pilots are supported by organizations like the Texas Produced Water Consortium [101].
- In Pennsylvania, produced water is similarly high in salinity to Alberta's formations, but less prone to souring. This drives operators to emphasize advanced solids-management processes, such as chemical precipitation, before blending to achieve the produced water quality required for recycling.
- In Colorado, TDS is much lower than in Alberta's formations, and producers are adopting modular treatment systems that extend beyond filtration to enable long-term beneficial reuse outside of the oil and gas sector, based on HB23-1242.

In the U.S. jurisdictions analyzed, closed loop produced water recycling for drilling and completion in hydraulic fracturing considers produced water as an industrial fluid, with treatment protocols that are primarily operational and focused on containment (i.e., fit -for-purpose). For centralized processing facilities, certain jurisdictions like Pennsylvania have established regulatory frameworks whereby processed water may be classified under less restrictive categories (i.e., non-waste) if it meets specified water quality criteria [73].

When H_2S is present in produced water, producers rely on scalable treatment technologies to achieve the desired produced water quality for recycling. By integrating H_2S treatment technologies, producers can minimize environmental and human risks of produced water recycling and maintain compliance with regulations. As a comparison, Table 5 summarizes H_2S treatment methods used in the Permian Basin to address sour water concerns. Note that mobile/modular treatment units are commonly deployed at various sites to sweeten sour gas and produced water, offering flexibility for changing volumes and locations [102].

Table 5. Sour water treatment methods used in the Permian Basin.

Method	Status	Description
Oxidation and coagulation	Widely used	Used to oxidize H_2S into precipitable sulfates (e.g., ClO_2 oxidation) [95].
Automated scavenger dosing	Widely used	Chemical dosing systems automatically adjust produced water treatment based on real-time water quality and volume, improving efficiency and consistency [103].
Nitrate addition for microbial control	Piloted	Nitrate compounds are added to storage ponds to suppress bacteria that reduce sulfates into H_2S, lowering overall concentrations [104].

Anecdotally, one of the producers interviewed (Section 4.1.2) recognized that their operations already employ some of the treatment systems shown in Table 5 to meet acceptable H_2S concentrations for produced water recycling. Alberta producers generally rely on low capacity, fit-for-purpose systems focused on H_2S scavenging, salinity, solids management, and polishing, rather than the high-capacity treatment trains and blending more commonly employed in U.S. jurisdictions.

8. Conclusions and Recommendations

The comparative review of water management practices across North America's major shale formations hints at an emerging shift in the HF industry: produced water can be regarded as a means to improve long-term water security, particularly in arid regions. While the core process stages of water management (i.e., water sourcing, use, recovery of produced water, recycling, and disposal) remain consistent across regions, the ways in which these stages are executed vary based on localized geography and geology, basin-specific produced water chemistry, and evolving regulatory frameworks. In Alberta, while the WCP aims to reduce reliance on HQNS water, it is not generally perceived by producers as the principal factor influencing decisions around produced water treatment or recycling. Instead, other regulatory considerations tend to shape water management strategies, including environmental performance and sustainability goals and AER requirements for produced water storage design requirements and blending specifications for stored produced water.

Despite the identified barriers to produced water recycling in Alberta, many producers are exploring it to improve water supply reliability and reduce reliance on disposal infrastructure. Ongoing barriers to increased produced water recycling include the capital requirements for new infrastructure, the relatively low produced water yields of the Montney and Duvernay formations, and the added complexity of treating high-salinity and sour produced water. Informed by the preceding interviews and analysis, the activities below are recommended to further reduce the barriers to produced water recycling in Alberta:

1. Engage the AER on regulations that most materially influence the economics of produced water recycling, particularly the storage capacity and duration limits set by AER D055 and the blending requirements during storage outlined in AER D058 and the Waste Control Regulation.
    a. AER D055: Increasing the allowable capacity and storage duration of AWSS would enable producers to accumulate sufficient volumes for new fracturing operations, while also providing the operational flexibility needed to facilitate future produced water sharing between operators. Additionally, primary and secondary containment requirements for AWSSs and ECPs could be updated to reflect best practices observed in other jurisdictions while reducing overall costs for implementation.
    b. AER D058 and Waste Control Regulation: Both the Waste Control Regulation and D058 do not allow for dilution of waste by adding any solid or liquid to avoid regulatory requirements.
        i. Co-developing a risk-based protocol for the safe storage of blended water which incorporates monitoring, tracking, and emergency response plans,

would further enable the accumulation of meaningful produced water volumes for recycling.

c. Proposals to amend both directives and regulation could leverage performance data from produced water impoundments in Colorado, New Mexico, and Texas, along with secondary containment practices used in Colorado, New Mexico, Texas, and Pennsylvania, to develop Alberta-appropriate safeguards that support larger on-site or centralized storage for produced water, including blends.

2. Create a shared, voluntary, anonymized data and industry-led benchmarking program for produced water.
    a. The program's purpose is to support decision-making and risk-screening, including identification of sites where produced water recycling is not viable. A data-sharing program would allow producers to monitor aggregated peer data and identify produced water composition trends, recovery volumes, and shared challenges.
        i. Access to broader produced water composition datasets could support assessments of formation chemistry compatibility and help both producers and water management midstreamers evaluate the feasibility of centralized recycling hubs and fit-for-purpose treatment technologies.
    b. The proposed initiative would be governed independently from regulatory compliance reporting requirements and would not to be used for enforcement.
        i. Sharing similarities with this approach, the AER Water Use Performance report provides company-level HF produced water use data, but it does not provide water quality, is not anonymized, and is part of regulatory compliance.
3. Leverage data sharing and benchmarking program's data to coordinate industry-led bench-scale, pilot-scale, or field-scale pilots and develop H_2S and salinity treatment technologies under Alberta-specific conditions. Pilot results, including ranges for capital and operating costs and produced water quality outcomes, would be shared between participants.
    a. The AUPRF, funded voluntarily by over 300 producers through an annual levy, supports applied research by universities, operators, and consultants to address high-priority environmental issues facing the upstream industry. The AUPRF operates as an industry-led counterpart to the Produced Water Consortiums established in the United States and could be leveraged to develop produced water H_2S and salinity treatment pilots.

i. Under the Water Innovation Planning Committee (WIPC), AUPRF has recently issued a request for proposal on produced water treatment in H_2S environments in pilot phase.

b. Other similar initiatives have taken place in Alberta, including the Canadian Emissions Reduction Innovation Consortium (CanERIC), led by PTAC, and the Water Technology Development Centre (WTDC). In both cases, industry guided the work, with Alberta Innovates contributing a portion of the funding.

i. CanERIC uses an industry-driven platform to identify key challenges and test new technologies to address and reduce risks associated with methane emissions through coordinated lab and field trials with academic and institutional partners.

ii. The WTDC was a joint venture by Suncor Energy Inc., Canadian Natural Resources Limited, Cenovus Energy, and the China National Offshore Oil Corporation, supported through funding from Alberta Innovates' Clean Technology Facilities Support Program and Water Innovation Program.

4. Integrate water lifecycle considerations into producers' economic models.

a. Existing economic models may not fully account for the complete water lifecycle in HF operations, which can make produced water recycling appear more costly than current water management practices. To address this gap, AUPRF could facilitate the development of standardized economic models that consider all stages of the water lifecycle, including risk-adjusted costs such as probability-weighted production impacts, regulatory risk, disposal constraints, and reputational exposure.

i. Incorporating producer input, including the sharing of operational data and best practices, would support more robust model calibration and enable a more accurate valuation of water across its full lifecycle, beyond capital and operating expenditures.

The strategies cited above have the potential to facilitate broader adoption of produced water recycling in Alberta by addressing sources of uncertainty and mitigating risk, rather than imposing prescriptive requirements, consistent with Alberta's established tradition of industry-driven and risk-based approach to water management.

9. Closure and Limitations

This report has been prepared for the exclusive use of Petroleum Technology Alliance Canada (PTAC) for specific application to the project described herein. The analysis and recommendations represent the best judgment of WaterSMART Solutions Ltd. (WaterSMART) based on the information available at the time of this report.

The primary objective of this report is to examine the practical and regulatory influences on the economics of produced water recycling in Alberta compared to four North American jurisdictions. This report is structured around two main elements: a research component and an interview component. The research was carried out following WaterSMART's assessment methods and established procedures, consistent with the parameters outlined in the scope, data sources, and jurisdictional comparison framework sections. The interview component brings together professional perspectives and insights from external subject matter experts. WaterSMART's responsibility is limited to ensuring the accuracy and integrity of our own research and faithfully representing the input from interviewees; we do not assume responsibility for the completeness or correctness of external opinions provided through interviews. Preparation of this report has adhered to APEGA recognized professional standards and industry best practices.

Respectfully submitted,

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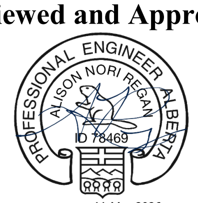

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WaterSMART Solutions Ltd.

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RM APEGA ID #: 124995
DATE: March 11, 2026
PERMIT NUMBER: 11413
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Appendix A

Interview Questionnaire

Section 1: Company Profile and Water Management Approach

1. How would you describe your organization's overall approach to water management in hydraulic fracturing?
   a. In which regions/formations does your company operate in?
2. What are your organization's main sources of water for hydraulic fracturing? (e.g., high-quality nonsaline [HQNS], produced water, municipal effluent, etc.)

Section 2: Experience with Water Recycling

3. Can you describe any water recycling initiatives or practices your organization has implemented?
   a. What motivated these initiatives (e.g., economics, regulation, stakeholder pressure)?
   b. Can you share a specific example or story that illustrates your approach?
4. How would you characterize your organization's water recycling rate (e.g., percentage of produced/flowback water recycled vs. disposed)?
   a. Two years ago, we compiled data regarding obstacles to recycling. Factors such as convenient access to HQNS water, as well as the costs associated with disposal, storage, treatment, and conveyance, were identified as significant barriers within Alberta. Has there been a substantial shift in this landscape since that time?

Section 3: Drivers, Barriers, and Economics

5. What are the main drivers that encourage your company to recycle water or use alternative sources? (e.g., cost savings, regulatory requirements, ESG goals, freshwater scarcity)
6. From an economic perspective, what are the key costs associated with water recycling in your operations?
   a. How do these compare proportionally to the costs of water disposal?
   b. Are there operational or economic thresholds (e.g., minimum produced water volume, water quality) that make recycling viable or not viable?
7. Has your company realized any cost benefits from increased water recycling? (e.g., reduced disposal, freshwater acquisition, conveyance, or capital expenditures)

   a. If so, which benefits have been most significant?

Section 4: Regulatory and Policy Environment

8. How has Alberta's regulatory environment influenced your company's water recycling practices?
   a. Are there specific regulations or policies that have enabled or hindered recycling?
   b. How does Alberta compare to other jurisdictions where you operate or have knowledge (e.g., BC, Texas, Colorado, Pennsylvania)?
9. Have you encountered any regulatory or permitting challenges related to water recycling infrastructure (e.g., storage, conveyance, treatment)? For example, D055 (storage), D058 (waste management) or D077 (pipeline conveyance).
   a. How have you addressed these challenges?
10. Are you aware of legislative or policy developments in other jurisdictions that you think could be relevant for Alberta?
   - For example:
   • In Colorado, a Bill was recently proposed to mandate a target increase in water recycling for hydraulic fracturing, aiming for 35% by 2038, with a credit trading system for producers who exceed the target.
   • In Pennsylvania, limited disposal well capacity has been a major driver for increased water recycling in hydraulic fracturing operations.
   a. How might similar policies or constraints, if implemented or experienced in Alberta, impact your company's operations or water management strategy?
   b. Do you see potential for such approaches (mandates, incentives, or constraints) to be effective or problematic in the Alberta context?

Section 5: Future Outlook, Incentives, and Trends

11. What types of incentives (financial, regulatory, reputational) would most effectively encourage your company to increase water recycling?
   a. Are there policy changes or programs you would recommend?
12. How might emerging trends, such as competition for pore space (e.g., due to carbon capture and storage) or low surface water streamflow, affect your water management and recycling decisions in the future?

Section 6: Lessons Learned and Best Practices

13. What lessons has your company learned from implementing (or attempting to implement) water recycling or alternatives to HQNS water?

   a. What would you do differently if starting again?

14. Are there best practices or innovations from other regions or companies that you believe could be successfully adopted in Alberta?

Appendix B

Alberta Energy Regulator – Relevant manuals and directives

For the HF industry, Alberta operationalizes its policy, including the WCP, through a suite of AER manuals and directives. The AER's guidance and requirements directly impact how HF produced water is stored, conveyed, treated, and disposed of [105]. Summaries of the most impactful regulatory instruments are provided below. In addition, operators in Alberta must also comply with other Provincial statutes, such as the *Oil and Gas Conservation Act* and the *Environmental Protection and Enhancement Act*, which collectively provide the framework for the orderly and responsible development of oil and gas resources and minimize potential negative impacts on water resources [106, 107]. For further details regarding water-related regulatory instruments relevant to hydraulic fracturing in Alberta, consult WaterSMART's 2024 report [2].

Manual 025: Applications under the WCP

Manual 025 assists operators in applying for, renewing, and amending water licences under the *Water Act* and the WCP. The manual supports the WCP's objectives by ensuring that all reasonable alternative water sources have been assessed for technical and economic feasibility to conserve HQNS water. More specifically, the manual outlines a tiered, risk-based assessment process and a structured alternatives evaluation, including confirmation, screening, and detailed stages, that applicants are required to complete when requesting HQNS water. It clarifies distinctions among water categories (i.e., HQNS and alternatives to nonsaline sources) and highlights considerations relevant to conservation efforts [108, 109].

Directive 077: Pipelines – Requirements and Reference Tools

Directive 077 was first issued in 2011, amalgamating information about pipelines from various directives, informational letters, interpretive documents, and reference documents into a single directive. D077 outlines the testing and operational requirements for ensuring pipelines, whether permanent or temporary, are operated safely and in accordance with regulations and industry standards. As it pertains to water, the directive addresses:

- External corrosion prevention coatings under pipeline insulation.
- High-performance high-density polyethylene pipe in oil and gas service.
- Pipeline pressure testing using liquid media other than HQNS water and gaseous test media.
- Temporary surface pipelines for well testing, bypass, or water conveyance.

Notably, for temporary surface pipelines for water conveyance (TSPW), D077 sets a limit for the duration a TSPW can be used for (i.e., 12 months and up to a 12-month extension afterwards) and defines three separate water groups for conveyance based on a set of criteria (i.e., composition and potential environmental impact of a spill). This water group classification governs approval pathways, deployment, routing, surveillance, emergency response procedures, and technical requirements. Produced water and mixtures fall into the higher risk group (i.e., 3), requiring the most stringent technical and operational risk mitigation.

D077 also establishes that water containing constituents at levels that could be an immediate human health hazard if released is prohibited from being conveyed through a TSPW, including water with extreme pH (i.e., ≤2 or ≥11.5) or water with unsafe levels of hydrogen sulphide (H_2S), naturally occurring radioactive materials, or flammable or explosive constituents [89].

Directive 055: Storage Requirements for the Upstream Petroleum Industry

Directive 055 defines the design, secondary containment, leak detection, and siting requirements for produced water storage systems used, such as engineered containment ponds (ECPs), aboveground synthetically lined walled storage systems (AWSSs), and above ground or underground storage tanks and containers. The latest iteration of D055, issued in 2024, indicates that as industry decreases the use of HQNS water to align with the WCP, the use of alternative water is increasing, as is the need for larger capacity storage systems, such as ECPs and AWSSs [82].

Notably, some provisions of D055 indicate that stored materials are expected to be actively used and not remain in one place for longer than one year. D055 also establishes that the maximum capacity of a single AWSS must not exceed 6,600 m^3 and the collective capacity on site must not exceed 30,000 m^3.

Directive 058: Oilfield Waste Management Requirements

Directive 058 establishes the guidelines for classifying, handling, treating, reusing, and disposing of oilfield waste. According to D058, waste storage and waste transfer activities are defined as the collection and storage of waste until sufficient volume is available for cost-effective transfer to a facility for treatment, processing, recycling, or disposal. When any volume produced water, flowback, or leachate are recycled as alternatives to HQNS water in HF, the responsible party is required to obtain approval for an oilfield waste management facility that includes a waste storage activity. D058 defines dangerous and non-dangerous oilfield waste (i.e., DOW and non-DOW) according to the parameters set forth in the Waste Control Regulation under the Environmental Protection Enhancement Act. Both D058 and the Waste Control Regulation indicate that waste must not be diluted to avoid regulatory requirements.

Produced water, including brine solutions, are commonly classified as non-DOW, but may be a DOW based on its properties. Furthermore, D058 defines that blending produced, flowback, or leachate water with nonsaline water must only occur prior to conveyance or immediately before HF operations, and not during storage. Water being stored for reuse must be managed as waste until it has been used [110].

Directive 051: Injection and Disposal Wells

Directive 051's purpose is to ensure wellbore integrity during injection or disposal operations. D051 provides:

- Criteria to determine well class for injection or disposal of fluids.
- Requirements for completion, logging, testing, and monitoring for each well class.
- Information required for submission in support of an application for approval to inject or dispose of fluids subsurface.

Although D051 is not a recycling-specific directive, disposal availability and standards materially impact the economics of produced water recycling for operators [53].

Appendix C

Matrix comparison – Qualitative evaluation in-depth framework

This appendix provides further details on the dimensions of the qualitative, matrix-based comparison used in this analysis.

HQNS water policy stewardship

HQNS water policy stewardship refers to the regulatory and operational structures that govern the sourcing, prioritization, and management of HQNS water in HF operations. HQNS water policy stewardship was evaluated based on the following criteria:

- Policy framework: The comprehensive set of laws, regulations, and guidelines that direct the sourcing and utilization of HQNS water in HF operations.
- Preference hierarchy: A policy- or regulation-defined order for water sourcing that prioritizes recycled produced water, saline water, or municipal effluent over HQNS water to guide operations and ensure compliance.
- Operational reality: The practical application of HQNS water stewardship in daily operations, including accessibility of HQNS water, challenges with alternatives, and how effectively policy goals are met.
- Incentives and barriers: The financial, regulatory, and logistical factors that encourage or discourage the use of HQNS water alternatives.
    - Incentives may include grants or royalty credits, while barriers can involve high costs, regulatory complexity, or infrastructure limitations.

Produced water recycling constraints

Recycling constraints refer to factors that influence how produced water is managed after recovery. More specifically, this qualitative factor is defined by the following criteria:

- Disposal infrastructure: Physical assets and systems available for disposal and recycling of water, such as injection wells, treatment facilities, pipelines, and storage units. Infrastructure capacity and proximity directly affect operational flexibility and cost.
- Disposal regulatory considerations: Legal frameworks governing produced water disposal and recycle, including permitting requirements, environmental standards, and limitations on discharge or injection.

- Operational impact: Description of disposal and recycling constraints on day-to-day operations, including scheduling, logistics, water management strategies, and the need for produced water recycling or alternative sourcing solutions.
- Cost and logistics: Financial and logistical considerations of produced water disposal and recycle, such as conveyance distances, disposal fees, capital infrastructure investment, and overall operational costs.
- Environment, safety, and reputation: Environmental and health risks associated with water disposal and recycle, including groundwater protection, induced seismicity, spill prevention, and management of hazardous components (e.g., Hydrogen Sulfide - H_2S concentration in produced water).

Produced water management

Produced water management refers to the additional stages in Figure 4 aimed at facilitating produced water recycling. The following criteria were considered:

- Access: Refers to sourcing water for HF operations, including produced and alternative water sources. Access is subject to physical availability, regulatory approval, and logistics.
- Storage: Refers to methods and infrastructure used to hold produced water prior to recycling or disposal. Storage elements include synthetically line walled storage systems (AWSS), engineered containment ponds (ECPs), and above ground or underground storage tanks and containers, as well as considerations for regulatory compliance, capacity, and site management.
- Treatment: Refers to processes and technologies applied to produced water to meet quality standards required for recycling. Treatment may address contaminants such as total dissolved solids (TDS), H_2S, bacteria, and scaling agents, and includes both on-site and off-site solutions.
- Conveyance: Refers to the transport of water between sources, storage, treatment facilities, and well sites. Conveyance methods include trucking, pipelines, and TSPW, with attention to cost, distance, regulatory requirements, and risk management.