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UNCONVENTIONAL SOURCES OF WATER FOR NEW MEXICO: OPPORTUNITIES AND CONSTRAINTS

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A White Paper by Bruce M. Thomson

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Abstract

Decreasing supplies and increasing demand for fresh water have led to consideration of unconventional sources of water to meet the needs of New Mexico. Unconventional sources include: wastewater reuse, stormwater capture and reuse, desalination of brackish groundwater, and desalination of produced water from oil and gas production. The principal challenges associated with these sources include the following.

Reusing wastewater will reduce its discharge, which will affect downstream deliveries and may impact a community's water rights. New Mexico does not have regulations governing potable or non-potable reuse, although there are guidelines for non-potable reuse.

Stormwater capture and use requires a water right, except for on-site capture. Capturing runoff in existing reservoirs requires reconstructing stormwater dams and enlarging reservoir volumes, which may not be feasible in urban watersheds.

Pumping groundwater from deep (greater than 2,500 ft) brackish aquifers does not require a water right although shallower groundwater development does. The challenges of developing brackish groundwater are significant. Furthermore, impacts on other groundwater resources must be considered.

Large volumes of produced water are generated by oil and gas production. Its treatment and use does not require a water right, but its salinity averages three times that of seawater. Large-scale desalination has not yet been demonstrated but research suggests it is feasible; thus, it may constitute a future source of fresh water.

Keywords: wastewater reuse, stormwater capture, brackish groundwater resources, produced water reuse

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Acronyms and Abbreviations

ABCWUA	Albuquerque Bernalillo County Water Utility Authority
AF	acre-feet
AF/yr	acre-feet per year
AMAFCA	Albuquerque Metropolitan Arroyo Flood Control Authority
ASR	aquifer storage and recovery
AWWA	American Water Works Association
BAF	billion acre-feet
BRACS	Texas Brackish Aquifer Characterization System
BTEX	benzene, toluene, ethylbenzene, and xylene compounds
CAPEX	capital expenditure
CAS	Chemicals Abstract Service
CBM	coal bed methane
CECs	contaminants of emerging concern
cfs	cubic feet per second
CODWR	Colorado Department of Natural Resources
COGCC	Colorado Oil and Gas Conservation Commission
COPWR	Colorado Produced Water Consortium
CWA	Clean Water Act
DPR	direct potable reuse
EBID	Elephant Butte Irrigation District
EDR	electrodialysis reversal
ELG	effluent limitations guidelines
EMNRD	New Mexico Energy, Minerals, and Natural Resources Department
EOR	enhanced oil recovery
EPA	U.S. Environmental Protection Agency
FD	freeze distillation
FO	forward osmosis
GAC	granular carbon adsorption
GSI-LID	green stormwater infrastructure and low impact development

GWPC	Ground Water Protection Council
GWQB	Ground Water Quality Bureau, New Mexico Environment Department
IPR	indirect potable reuse
ISC	New Mexico Interstate Stream Commission
IX	ion exchange
KBH	Kay Bailey Hutchison Desalination Plant
KAF	thousand acre-feet
LRV	logarithmic reduction value
M	million
MAF	million acre-feet
MAR	managed aquifer recharge
MBR	membrane bioreactor
MD	membrane distillation
Mgal/d or mgd	million gallons per day
Mgd	million gallons per
mg/L	milligrams per liter
MRED	mineral recovery enhanced desalination process
MRG	Middle Rio Grande
MRGCD	Middle Rio Grande Conservancy District
NAWAPA	North American Water and Power Alliance
NDC	North Diversion Channel
NF	nanofiltration
NMAC	New Mexico Administrative Code
NMBGMR	New Mexico Bureau of Geology and Mineral Resources
NMED	New Mexico Environment Department
NMAC	New Mexico Administrative Code
NMOCC	New Mexico Oil Conservation Commission
NMOCD	New Mexico Oil Conservation Division
NMOSE	New Mexico Office of the State Engineer
NMPWRC	New Mexico Produced Water Consortium
NMSA	New Mexico Statutes Annotated

NOI	notice of intent
NORM	naturally occurring radioactive material
NPDES	National Pollutant Discharge Elimination System
NPR	non potable reuse
NRC	National Research Council
NTU	nephelometric turbidity units
NWRAP	National Water Reuse Action Plan
NWRI	National Water Research Institute
O&G	oil and gas
O&M	operation and maintenance
OM&R	operation, maintenance, and repair
OPEX	operational expenditure
PER	preliminary engineering report
PFAS	per- and polyfluoroalkyl substances
PMD	photocatalytic membrane distillation
PW	produced water
RCRA	Resource Conservation and Recovery Act
RGTIHM	Rio Grande Transboundary Integrated Hydrologic Model
RO	reverse osmosis
RRC	Texas Railroad Commission
RSIJHM	Rio San Jose Integrated Hydrologic Model
S	storativity
SAG	San Andres Limestone-Glorieta Sandstone aquifer
SDWA	Safe Drinking Water Act
SOR	secondary oil recovery
SWD	salt water disposal
TCEQ	Texas Commission on Environmental Quality
TDS	total dissolve solids
TEA	techno-economic assessment
TENORM	technically enhanced naturally occurring radioactive material
TERS	total estimated recoverable storage

TOC	total organic carbon
TPWC	Texas Produced Water Consortium
TSS	total suspended solids
TWDB	Texas Water Development Board
UF	ultrafiltration
UIC	underground injection control
USGS	United States Geological Survey
USR	underground storage and recovery
UV	ultraviolet
UV-AOP	ultraviolet advanced oxidation process
VMD	vacuum membrane distillation
VOC	volatile organic compounds
VSEP	vibratory shear enhanced processing
WET	whole effluent toxicity
WOTUS	Waters of the United States
WQCC	New Mexico Water Quality Control Commission
ZLD	zero liquid discharge

Executive Summary

Recognition that nearly all of New Mexico's fresh water resources are fully allocated and that a warming climate will cause future water supplies to decrease while future demand will increase has led to much interest in identification and development of new sources of water. This interest has been in part formalized with the publication of the 50-Year Water Action Plan by the Office of the Governor of New Mexico in 2024. The plan identifies three priority actions: increase water conservation, identify and develop new water supplies, and implement programs to protect the quality of the state's watersheds and water resources. Three potential new water sources are listed in the Action Plan: reuse municipal and industrial wastewater, develop brackish groundwater resources, and desalinate very high salinity wastewater generated by oil and gas (O&G) production, that is, produced water (PW) for subsequent reuse. A fourth unconventional source not mentioned in the Action Plan but identified in other local and national water resource planning programs is the capture and reuse of stormwater runoff from urban watersheds.

This white paper reviews the technical, hydrologic, and regulatory feasibility of using each of these four unconventional sources of water to augment existing supplies. It is based on reviews of publicly available information and provides context that helps to understand the opportunities and constraints for utilizing these sources to help meet water demands in New Mexico. A summary of the findings is presented below.

<u>Wastewater Reuse:</u> There is a large and growing body of scientific and engineering literature on treating municipal and industrial wastewater for reuse that includes non-potable reuse (NPR) for irrigation and industrial purposes, indirect potable reuse (IPR), and direct potable reuse (DPR) for drinking water supply. Key points when considering wastewater reuse include:

- Water rights in New Mexico are based on consumptive use of water, the difference between the amount of water diverted and the amount returned to the environment. Many water utilities in New Mexico receive return flow credits for treated wastewater that is discharged to streams or rivers, hence reducing this discharge by increasing wastewater reuse will increase the utility's consumptive use suggesting it will likely have to acquire additional water rights in order to reuse the wastewater for non-potable or potable purposes.
- Wastewater discharged to a river or stream is a source of water for downstream users and may provide environmental services for aquatic and riparian habitats important to endangered species and public recreation.
- New Mexico does not have regulations that govern reuse for either NPR, IPR, or DPR. However, the technologies for treating wastewater to drinking water quality are well developed and other states including California and Colorado have well developed potable reuse regulations that could serve as a template for New Mexico standards.

In some cases, it may be less expensive for a utility to reuse its wastewater than treat it to a very high quality to meet stringent discharge requirements. If a community does not receive return flow credits, has available water rights, or can acquire additional water rights, municipal wastewater can be a reliable source of wet water to supplement existing supplies.

Stormwater Capture and Reuse: Urban storm runoff is highly visible and it is easy to imagine its capture and reuse. This makes it an attractive source of water that has been considered in many local and regional planning programs. Key points when considering stormwater capture and reuse include:

- In New Mexico once stormwater leaves one's property it becomes waters of the state and cannot be detained for longer than 96 hours according to state water law. Onsite stormwater capture and reuse is allowed in New Mexico and is an important component of green stormwater infrastructure and low impact development (GSI-LID). However, offsite stormwater capture and reuse requires obtaining a water right, which can be challenging in fully appropriated surface watersheds.
- Stormwater is a source of water for downstream users and provides environmental services for aquatic and riparian habitats that support threatened and endangered species and provide public recreation. Downstream users may be entitled to this water under their water rights.
- Urban flood control dams are not designed to retain a pool of water for later release. These dams do not have operable gates to allow controlled release, do not meet geotechnical criteria to retain water, and do not have sufficient capacity to provide for both flood protection and storage for later use. If urban stormwater reservoirs are modified to include stormwater capture and storage for reuse, the dam must be raised and the inundation pool enlarged which will have financial and land use consequences.
- Few urban stormwater reservoirs are located near points of use. Transporting water to irrigation systems or water treatment facilities may require costly new infrastructure in the form of pipelines or canals.
- Stormwater capture followed by controlled release to sand bottom arroyos may provide a method of aquifer recharge.
- Urban runoff quality is poor and may require treatment before it can be used for beneficial use purposes.
- The volume of stormwater that might be captured in urban areas for subsequent use is relatively small compared to local demand for new supply.

It is conceivable that there may be situations where stormwater capture, storage, and use might be feasible. An example is presented in this paper of an undeveloped watershed in Doña Ana County, below the delivery point of water to the Lower Rio Grande and Texas under the Rio Grande Compact. However, the regulatory and engineering challenges of increasing the inundation pool and raising and reconstructing the dam to store water would be substantial.

Brackish Groundwater: New Mexico has large volumes of undeveloped brackish groundwater. Until 2009, groundwater with a total dissolved solids (TDS) concentration greater than 1,000 mg/L from an aquifer where the top of the aquifer is greater than 2,500 ft deep was not subject to jurisdiction by the New Mexico Office of the State Engineer (NMOSE). Jurisdiction over this water was granted in 2009, but by then over 700 Notices of Intent (NOIs) to divert this water had been filed. The quantity of deep brackish water is not known though a frequently cited approximation is 3 billion acre-ft. Such a large volume of water is the impetus for the 50-Year Water Action Plan's recommendation to develop this resource. Key points when considering development of deep brackish groundwater resources include:

- There is little quantitative knowledge of deep brackish water aquifers including their extent, hydrogeologic properties, volume of recoverable water, and water quality.
- Deep aquifers have poor hydrogeologic properties (i.e., transmissivity and storativity), drilling costs and pumping costs will be high, and many widely spaced wells will be required to produce large volumes of water. Wells drilled in these formations will have low yields.
- Deep aquifers receive little or no recharge and therefore do not constitute a renewable or long-term source of supply. If pumping from a deep aquifer impacts overlying aquifers or surface water, the project will be required to obtain water rights to offset this impact.
- The chemistry of deep brackish groundwater is complex and will make desalination difficult and costly.
- Desalination produces a waste stream containing high concentrations of salts, metals, radionuclides, and other constituents requiring disposal. The presence of metals and radionuclides may cause the waste to be a hazardous and/or a radioactive waste that will greatly increase management and disposal costs.

A case study is presented of a proposed project to use deep brackish groundwater for a new community in Sandoval County with an ultimate population of 309,500 people. An analysis shows that the aquifer would provide water supply for between 30 and 90 years depending on the population growth scenario and the varying estimates of the volume of recoverable water. The question is posed: What will this community do for water supply after the aquifer is depleted?

Despite the large number of NOIs that have been submitted to pump deep brackish groundwater, fewer than 60 wells have actually been drilled, mostly to supply brackish water for the oil and gas industry. This is in part a reflection of the costs and complexity of developing this resource. Deep brackish water may provide water for future industrial or agricultural uses, but because it is not renewable, it should not be used as a source of supply for municipal development but may be appropriate for industrial or agricultural use.

Although the focus of this discussion is on deep brackish aquifers because they can be developed without acquiring a water right, there are also shallow brackish and saline aquifers in New Mexico that may provide water supply in some areas. Two such aquifers are the Mesilla Conejos-Médanos aquifer in Doña Ana County and the Tularosa Basin in Otero County. Both are discussed in this report.

<u>Produced Water from Oil and Gas (O&G) Development:</u> New Mexico is the second largest O&G producing state in the country. A very large volume of PW is generated annually, approximately 324,000 acre-feet (AF) in 2024, more than 98% of which is from the Permian Basin of southeastern New Mexico. This volume is dependent on O&G production and will increase or decline as production changes. Permian Basin PW is extremely saline with an average TDS concentration of greater than 120,000 mg/L. The TDS concentration of San Juan Basin PW is lower, averaging around 20,000 mg/L. Subsurface injection data reported to the New Mexico Oil Conservation Division (NMOCD) shows that roughly 75% of PW was disposed of by deep well injection in salt water disposal (SWD) wells in 2024 and 25% was used for enhanced oil recovery (EOR). A large but unreported volume was transported to Texas for disposal. Concerns about induced seismicity caused by deep well injection of large volumes of PW may limit this disposal option in the future. The very large volume of PW makes it an attractive potential

source of water if it can be desalinated. Laboratory and short duration pilot studies have demonstrated the ability to desalinate PW to a high quality. For Permian Basin PW, these systems are primarily based on thermal processes rather than membrane processes such as reverse osmosis due to its very high salinity. Several challenges remain to using PW as a source of supply. Key points when considering using PW as source of supply include:

- There is strong public opposition to reuse of PW based on concerns that it contains unknown toxic constituents that cannot be removed by treatment technologies. Recent studies of its composition and toxicity have found no unexpected contaminants after treatment that present exceptional hazards or toxicity.
- Treatment and reuse of PW outside of the O&G industry is currently prohibited in New Mexico and awaiting development of regulations and a permit process.
- The salinity and chemistry of Permian Basin PW is too complex for desalination by conventional seawater technologies such as reverse osmosis (RO). The technical challenges are a result of its very high salinity, high mineral scale potential, high corrosion potential requiring use of special materials, and production of hypersaline wastes that are difficult to manage and dispose.
- Wastes from PW will likely have high concentrations of toxic metals and radionuclides. Although there are exemptions in hazardous and radioactive waste regulations that apply to O&G exploration and production wastes, it is uncertain whether these will apply if the water is treated for use outside of the industry. Waste management and disposal will become more complicated if they are subject to hazardous and radioactive waste regulations. There is limited experience with long-term (greater than 6 months) pilot-scale PW desalination treatment plants, which introduces uncertainty regarding the implementation, performance, and life cycle costs of full-scale PW desalination projects.
- The few available cost projections suggest that PW desalination will be greater than the current cost of disposal by injection into salt water disposal (SWD) wells.

The technical challenges and high cost of treating Permian Basin PW for reuse suggest that its desalination and reuse is not likely to be implemented at a large scale unless it can be shown to be less expensive than the cost of disposal in SWD wells or other advantages can be identified. The increasing risks of induced seismicity from PW disposal has led to discussion of more stringent regulations over deep well injection that may limit PW disposal capacity and increase disposal cost. Increasing disposal costs together with improvements in the performance and cost reductions of PW treatment technologies will provide an economic advantage for PW treatment and reuse over disposal. New regulations based on a better understanding of treatment methods and quality of treated PW are needed to allow its reuse. It will be important to establish public support and new regulations to allow safe reuse of PW. Produced water is not a renewable source of water and therefore should not be relied upon as a source of supply for municipal development.

Perhaps the most important conclusion of the analyses in this paper is that each of the four unconventional sources of water considered is part of a complex hydrologic system that is subject to an intricate and interconnected network of regulatory, technical, public and environmental health, hydrologic, economic, and infrastructure systems that must be recognized when considering their development as a potential resource. The hydrologic limitations, regulatory constraints, and technical and economic challenges associated with each are substantial.

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Introduction

The constitution of New Mexico and subsequent state laws establish that all surface and groundwater resources belong to the public. A person or other entity can obtain a right to use this water for beneficial use (a concept that is not well defined), but the water is owned by the public. In the decades since statehood (1912) all of the surface water resources of the state have become fully allocated, which in principle means that the rights to use every drop of surface water in the state have been spoken for. New appropriations for groundwater can still be permitted in most basins except in Critical Management Areas and a few other basins where declining water levels or impacts on surface water resources require additional protection. Furthermore, most basins are considered to be over appropriated meaning that more water rights have been allocated (i.e., "paper water rights") than can be provided by actual wet water resources (Thomson, 2012). In other words, there is an insufficient amount of water to meet the demands of agriculture, communities, industries, and individuals who own the rights to use it. This lack of water resources was identified in the 2018 New Mexico State Water Plan and the shortfall was projected to increase so that by 2060 all water planning regions in the state are expected to experience water shortages even with imported water from the Colorado River Basin (NMISC, 2018) under existing agreements. These water shortages are projected to be greater than 700,000 acre-feet per year (AF/yr) in an average year and 2,400,000 AF/yr under drought conditions. To put these numbers in perspective, the total annual amount of surface and groundwater withdrawn in the state in 2020 was 3,800,000 AF (Valdez et al., 2024).

Future water shortages are expected to become more severe as a result of a warming climate (Dunbar et al., 2022). A review of the current state of knowledge suggests that both surface water runoff and groundwater recharge will decrease by 3% to 5% each decade resulting in an estimated decrease stream flow of 16% to 28% in the next 50 years (Phillips and Thomson, 2022). But the problem of fresh water shortages is not limited to a decreased supply. A warming climate will result in a longer growing season so that water demand for irrigated agriculture and urban landscaping will increase. Plant evapotranspiration rates and open water evaporation losses will also increase. These studies also suggest that there will be less winter snowpack and more rainfall in the mountains so that spring runoff will occur earlier in the year and there will be lower flows in the summer. All of these changes are already occurring and are impacting local water budgets. And to compound the shortages, population and economic growth will increase the water demand for municipal and industrial uses.

The traditional approach to increase a region's water supply has been to import water from neighboring watersheds. However, it is increasingly clear that all water planning regions in New Mexico are currently facing shortages that are expected to become more severe in the future (NMISC, 2018). Proposals to import water from neighboring states are problematic. Importation of water from the Colorado River basin into the Rio Grande watershed began with completion of three tunnels under the continental divide near the New Mexico-Colorado border in 1970, known as the San Juan-Chama Project, which allocated 98,600 AF/yr of water to the Middle Rio Grande. However, the Colorado River Compact, which divides water among the seven states in the basin was based on overly optimistic estimates of the annual flow in the river (Kuhn and Fleck, 2021). Continuing disputes over water allocations among states in the basin combined with diminishing flows resulting from a warming climate, make importing water from the Colorado River highly unlikely (Schmidt et al., 2023).

One of the most grandiose (some consider it to be outrageous) proposed projects was developed by the North American Water and Power Alliance (NAWAPA). This scheme, led by Lyndon LaRouche, a frequent presidential candidate during the middle part of the 20th century, was to divert water from rivers in the Canadian Rockies to the Rocky Mountain States and the western Great Plains of the U.S. (Schiller Institute, 2024). Looking to the east, more recent suggestions have been made to import water from the Mississippi River basin (Rehm, 2022) to eastern New Mexico or from the mouth of the Atchafalaya River (where the Mississippi discharges into the Gulf of Mexico) to the Colorado River (Siefkes and Muttardy, 2023). While both of these concepts involve enormous engineering challenges, would have very large energy requirements, and would be very costly, Thomson (2023) has pointed out that the real problem is that such proposals involve transporting large volumes of water over distances of 1,000 miles or more through arid parts of the country. Each state and region along the path of the canal would demand a share of the water from the project. Dividing up the supply among the states along the route of the canal would mean that very little water would ever make it to New Mexico. Thus, the combination of a limited available volume of water in contrast to the extraordinary demands of western states, coupled with the large engineering challenges and costs, make importing water from surrounding states highly unlikely.

To address the conflict between diminishing fresh water supplies and increasing demand there has been much interest in identifying “new” sources of water. They are referred to here as “unconventional sources of water.” These would be sources that have not been developed in the past and/or water resources that are not currently subject to state water law and therefore do not have water rights attached to them. Many ideas have been suggested, some more feasible than others. The unconventional water sources considered in this paper include: (1) reuse of municipal and industrial wastewater, (2) capture and reuse of urban stormwater, (3) desalinate and use of brackish groundwater, and (4) desalinate and use of produced water (PW) from oil and gas (O&G) production. Each of these sources has been mentioned in one or more of the 16 regional water plans prepared for the New Mexico Interstate Stream Commission (NMISC 2018). They have also been proposed by the EPA in its 2020 National Water Reuse Action Plan (NWRAP) (EPA, 2020). A study of the feasibility of desalinating brackish groundwater and produced water as a source of supply in New Mexico was done by NMED and ERG (2024).

A fifth proposal, namely, use of cloud seeding to increase snowfall in northern mountains, has also been suggested but is not reviewed here because the efficacy of the technology is uncertain and it is not considered in current state water planning. Furthermore, it seems likely that any new water from cloud seeding would be spoken for by existing water rights holders

All of these potential sources except stormwater capture and reuse are described in the 50-Year Water Action Plan (Grisham, 2025). At first consideration each of these options appears to offer sources of water that could be used to augment existing supplies. However, there has been little analysis or discussion of the regulatory and technical challenges that are associated with development and utilization of these unconventional water sources specifically in New Mexico.

This paper provides an in-depth analysis of the regulatory and technical issues associated with development of these unconventional sources of water. The feasibility of developing each unconventional source is summarized based on a review of recent available information on its quality, magnitude, and treatment requirements. Major technical challenges associated with developing each source are summarized and the regulatory constraints identified and discussed.

The purpose of this paper is to identify the regulatory and technical challenges that must be recognized and addressed when considering these resources as a potential source of water to augment existing supplies. The discussion of each is based on regulatory, hydrologic, and technical conditions in New Mexico. There is little discussion of the development of these resources in other states unless it is directly relevant to New Mexico. For example, both wastewater reuse and stormwater capture in California have fewer regulatory obstacles than in New Mexico because it is a coastal state with few downstream water delivery requirements. Therefore, experience in California offers little insight to developing these resources in New Mexico. Experience in the treatment and reuse of produced water (PW) from O&G development are the Niobrara basin of northeastern Colorado and the Kern River Oil Field near Bakersfield, California has little relevance to PW reuse in the Permian Basin of southeastern New Mexico because the water chemistry from these oil fields is quite different. Therefore, desalination technologies used to treat PW in California or Colorado may not be appropriate for treating PW from the Permian Basin.

This paper is not meant to be an exhaustive review of all of the knowledge about potential development and use of these unconventional sources, but rather a discussion of whether they have potential for future application in New Mexico. Most importantly, the paper identifies issues that must be recognized and addressed when considering each alternative as an option for supplementing a community's water supply.

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Wastewater Reuse

Introduction

There is increasing national interest on reuse and recycling of treated wastewater to meet municipal water demand and though there are about 100 such permitted facilities in New Mexico, none are used for potable water supply. It has been promoted by professional societies such as the WateReuse Association (WateReuse Association, 2024) and the American Water Works Association (AWWA, 2015), and has been the subject of studies by the National Research Council (NRC, 2012a, 2012b). It is strongly supported by the U.S. Environmental Protection Agency (EPA), which has summarized regulatory and technical advances in its National Water Reuse Action Plan (NWRAP) (EPA, 2020). One of the most complete references that describes the treatment technologies, potential reuse alternatives, and health risks of wastewater reuse is the book *Water Reuse: Issues, Technologies and Applications* by the engineering company AECOM (2007). Though its discussion of potable reuse regulations is somewhat dated, the discussions of health risks, reuse alternatives, and treatment technologies is complete, relevant, and applicable.

The principal benefits of wastewater reuse are to expand and increase the supplies of water in communities facing water shortages (NRC, 2012a) with the overlapping benefits of reducing wastewater impacts on receiving waters, increasing water security, sustainability, and resilience (Bryck et al., 2008; EPA, 2020; EPA and CDM Smith, 2017). The objective of EPA's NWRAP program (EPA 2020) is to "ensure that water reuse is accessible, straightforward to implement, and sensitive to climate and environmental justice considerations." A related but more pragmatic justification for wastewater reuse is that under many circumstances, it is less expensive to treat and reuse wastewater to drinking water standards than it is to purchase additional water resources (if they are even available), or treat poor quality water to drinking water standards (Duong and Saphores, 2015). Thus, for example, the City of San Diego has found that it is less expensive to purify and reuse its wastewater to supplement their potable supply rather than desalinate sea water (San Diego Public Utilities, 2024).

For inland communities in the arid southwest wastewater reuse may be the only source of wet water that is available to support the community needs (Scruggs and Thomson, 2017). Notable examples include El Paso, Texas (El Paso Water, 2024) and Big Spring, Texas. A local example is Cloudcroft, New Mexico, which built a water purification plant to supplement its limited groundwater supply, though it is not operational.

There are four types of municipal wastewater reuse:

- Non-Potable Reuse (NPR) – Treated wastewater is used for non-potable purposes such as industrial use, irrigation of crops, landscapes, and gardens.
- Unplanned (De Facto) Water Reuse – Treated wastewater is discharged to a stream or river and subsequently used as a source of supply for a downstream community. The presence of wastewater in the mixture is not considered when developing the source. This is sometimes referred to as unintentional or inadvertent reuse.
- Indirect Potable Reuse (IPR) – Reuse of highly purified wastewater that has been discharged to an "environmental buffer" (lake, stream, or aquifer) and then subsequently withdrawn for

water supply. This allows natural processes to further purify the water to improve its quality before it is reused. Indirect potable reuse is formally recognized as a form of wastewater reuse and states with reuse regulations have established standards for this source of supply.
- Direct Potable Reuse (DPR) – Highly purified wastewater is directly added to the treated potable water system. It may be blended with a conventional source of water or the purified water may be introduced directly into the potable water distribution system.

There are many examples of NPR in New Mexico. Perhaps the most common application is reuse of treated water for irrigation of landscapes, parks, golf courses, and playing fields, and for irrigated agriculture. There are about 100 groundwater discharge permits issued by the NMED for NPR projects in New Mexico (NMED Ground Water Quality Bureau data). Four notable examples of NPR in New Mexico are described here that illustrate the diversity in size and use of reclaimed wastewater:

- The Albuquerque Bernalillo County Water Utility Authority (ABCWUA) delivers highly treated water from its Southside Water Reclamation Plant to parks and golf course in the southeastern part of the City (ABCWUA, 2019).
- The City of Santa Fe uses about 1,300 AF/yr of reclaimed wastewater for recreation fields, golf courses, and to augment flow in the lower reaches of the Santa Fe River (Santa Fe, 2019).
- The City of Alamogordo uses all of its treated wastewater for irrigation of parks, ball fields, and urban landscapes (Alamogordo, 2024).
- The Village of Tularosa uses all of its treated wastewater to irrigate nearby orchards.

To date there is no direct potable wastewater (DPR) reuse in New Mexico. This section discusses the regulatory and technical issues that must be recognized when considering wastewater reuse by New Mexico communities.

Before this discussion, it should be recognized that municipal wastewater reuse does not by itself reduce consumptive use. This is explained in the following sidebar discussion.

Sidebar Discussion – Municipal Wastewater Reuse Isn't Necessarily Conservation

Although reuse of purified municipal wastewater is widely encouraged as a water conservation measure throughout the U.S. and indeed throughout the world, in New Mexico this isn't always the case. A discussion was provided by Thomson and Shomaker (2009) that is briefly summarized here.

In New Mexico, the rights to use water (i.e., water rights) are based on consumptive use which is defined as the difference between the volume of water withdrawn for use and the volume of wastewater returned to the environment. This can be written as a simple equation:

Consumptive Use = Volume of Withdrawal – Volume of Return Flow

Fundamentally, consumptive use is water that is lost to the atmosphere due to evapotranspiration from vegetation (lawns, trees, gardens, and urban landscaping) and evaporation such as that from swamp coolers, cooling towers, clothes drying, and industrial processes.

An example is presented here of water use in Albuquerque. In recent years, the ABCWUA has diverted an average volume of water of 100,000 AF/yr from a combination of groundwater and surface water sources and returned an average of 60,000 AF/yr of highly treated wastewater to the Rio Grande at the Southside Water Reclamation Plant (ABCWUA, 2019). Thus, consumptive use by the ABCWUA is 40,000 AF/yr. This situation is illustrated in Figure 1.

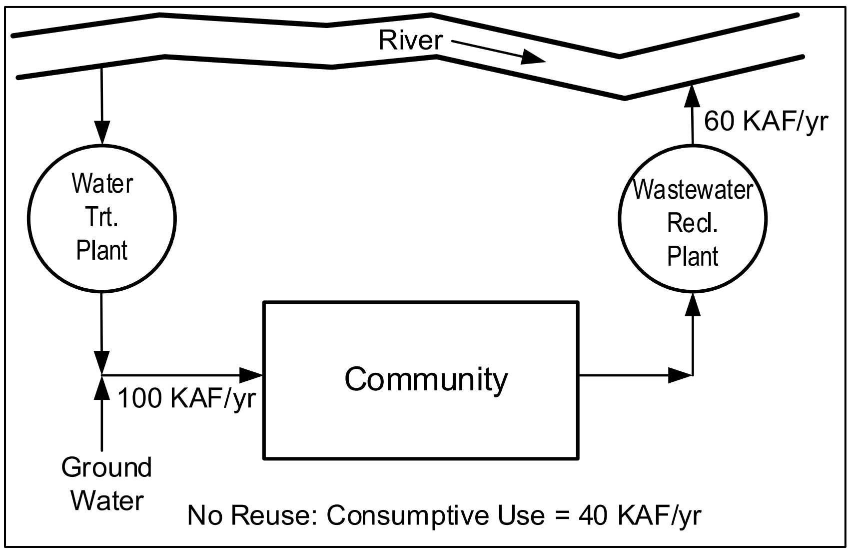

Figure 1. Illustration of consumptive use for a community where no wastewater is reused (KAF/yr means thousand AF/yr).

If the utility reuses one-third of its wastewater, 20,000 AF/yr, it can reduce its annual diversion by this same amount, so the total diversion is only 80,000 AF/yr. However, the consumptive use is still 40,000 AF/yr because it is returning less water to the river as shown in Figure 2. Note that in this scenario there is an environmental benefit in the form of an increased flow in the reach of the river between the intake for the surface water treatment plant and the discharge at the wastewater reclamation plant.

If the community does not receive return flow credits from its wastewater discharge, then there may be incentives to reuse this water rather than discharge it. For example, wastewater reuse may be a more reliable source of water or a less expensive source of water than other sources. This is especially true for coastal communities in arid regions such as southern California, which do not have return flow requirements. Another example are states, notably eastern states, which allocate water based on riparian rights (i.e., the proximity of the community to the river or lake) instead of priority date. Communities in such states may find that it is less expensive to purify and reuse their wastewater than to discharge it, hence reuse provides a way of augmenting their supply of usable water.

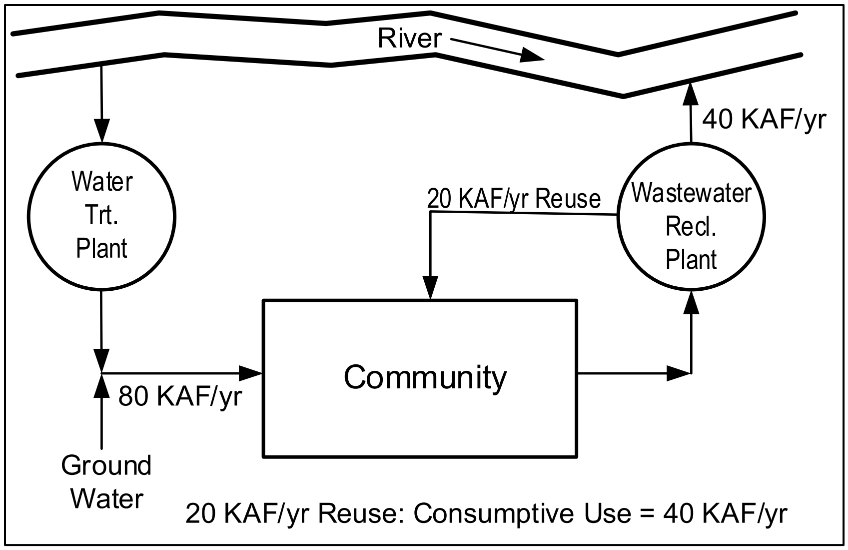

Figure 2. Illustration of consumptive use for a community where 1/3 of its wastewater is treated and reused (KAF/yr means thousand AF/yr).

There are several scenarios in which a New Mexico community may benefit from wastewater reuse even though it does not reduce its consumptive use:

- If the community has excess or unused water rights, reusing its wastewater may be less expensive than increasing the capacity of an existing supply or developing a new supply (i.e., constructing a new diversion and treatment, storage, and distribution system).
- If the community does not receive return flow credits, treating wastewater and reusing it in the community is a way of increasing supply. Some communities have not obtained return flow credits from the Office of the State Engineer. Many others, especially on the eastern side of the state, do not discharge to streams but rather to playa lakes and therefore return flow credits are not as meaningful.
- In some situations, it may be less expensive to reuse the wastewater than to treat it to a high degree to meet stringent discharge requirements. When a downstream Pueblo implemented strict stream standards, the City of Grants found that it was less costly to implement a total NPR program rather than upgrade their wastewater treatment plant to meet the new standards. Of course, this reduced delivery of water to the Pueblo which caused concern about impacts to its water supply (Lorenzo and Watchempino, 2003).
- Wastewater reuse may be justified when treated wastewater is the only source of wet water available to the community. This situation occurs in locations with limited or decreasing surface or groundwater resources such as occurs in some remote communities. For example, Cloudcroft, New Mexico is located near the top of the crest of the Sacramento Mountains in southeastern New Mexico with no surface water sources and small localized aquifers that provide an insufficient water supply, so that reuse is the only source of additional water supply for the community. Even under these circumstances the community must deal with state regulations regarding water rights and downstream delivery requirements.

There is another somewhat unique complexity in New Mexico that affects the feasibility of wastewater reuse: most wastewater discharges provide an environmental benefit by maintaining a flow of water in the stream. For example, the discharge from the ABCWUA Southside Water Reclamation Plant is the third largest tributary to the Rio Grande after the Rio Chama and the Conejos River (Thomson, 2012). During very dry summers, the river may have little or no flow near Albuquerque so that the only wet water in the river is effluent from the wastewater treatment plant. This discharge thus provides a benefit to the aquatic and riparian environment of the river and plays an important role in survival of endangered species such as the Rio Grande Silvery Minnow.

In addition to the water that wastewater reuse provides, it also increases the public's awareness of the value of the community's water. Parks with signs warning not to drink the water, and prominent purple plumbing fixtures (plumbing code for non-potable water), remind the public of how precious our water is and reinforces personal actions to preserve and protect this vital resource.

Regulatory Issues

There are two major regulatory issues governing the feasibility of wastewater reuse in New Mexico: (1) whether reuse will impact the user's water rights, and (2) what level of treatment will be required for the intended use.

<u>Water Rights Considerations:</u> The right to use water in New Mexico is governed by the Office of the State Engineer (NMOSE) and administered by the Water Resource Allocation Program (WRAP). In principle, the volume of a water right in New Mexico is based on consumptive use which, as described in the above sidebar discussion, is the difference between the amount of surface and/or groundwater diverted for use and the amount of wastewater returned to the environment. Whereas most water that is returned to surface or groundwater supplies are not measured, a utility receiving return flow credits is required to measure and report its wastewater discharges to the NMOSE (19.26.2.11(E) NMAC).

As described in the sidebar discussion, wastewater reuse does not reduce a community's consumptive use. Thus, for many projects wastewater reuse may not increase the usable water supply unless the utility can acquire additional water rights. Before planning any water reuse project, a community must work with the NMOSE to determine how the reuse project will impact their water rights.

If a community wishes to obtain return flow credits to enable it to increase its diversion, it must comply with rules regarding return flow credits that are contained in 19.26.2.11(E) NMAC. Approval of return flow credits is granted by the NMOSE. The rule states that return flows must be returned to the same surface or underground source from which it was appropriated. Thus, a utility that diverts surface water for its supply must return treated wastewater to the same stream, river, or lake, while a utility that uses groundwater must return its wastewater to the same aquifer. Return flow credits generally are not approved for incidental leakage from irrigation use, ponds, or onsite wastewater treatment and disposal systems (i.e., septic tank and leach field systems). A description of the regulations and procedures for obtaining return flow credits as well as several case studies of the process has been published by the NMOSE (2001).

Regulations Pertaining to Wastewater Discharges: With few exceptions, discharges of treated wastewater to surface waters are regulated by the EPA under part 122 of the Clean Water Act (CWA) and require a National Pollutant Discharge Elimination System (NPDES) permit (EPA, 2025). The exceptions are discharges to waters that are not Waters of the United States (WOTUS) as defined by the CWA. For example, discharges to playa lakes in eastern New Mexico do not require an NPDES permit. The permitted discharge water quality is established so that the treated effluent will not result in exceedance of the stream standards that are based on the designated uses of the water body. The stream standards are set by the state and approved by EPA.

In New Mexico, the NPDES program is administered by Region VI of the EPA which has issued about 100 NPDES permits in the state. The 2025 New Mexico legislature passed amendments to the state's Water Quality Act (74-6-2 NMSA) that allow the state to develop its own discharge permitting process in accordance with the federal CWA. Implementation of this process will require development of state regulations and identification of a mechanism to fund administration of the permit program.

In order to discharge treated wastewater to an underlying aquifer, the utility must obtain a groundwater discharge permit from the New Mexico Environment Department (NMED) according to rules contained in 20.6.2 NMAC. The treated water must comply with New Mexico groundwater standards listed in this rule that are very similar to federal drinking water standards. Treating water to this high quality may provide an incentive for the community to simply use the water for DPR rather than discharging it to receive return flow credits. Neither groundwater quantity nor quality is regulated by EPA except for special circumstances such as hazardous waste management under the Resource Conservation and Recovery Act (RCRA). Groundwater quality in New Mexico is regulated by the NMED under rules in 20.6.2 NMAC.

Underground storage and recovery (USR, also sometimes referred to as aquifer storage and recovery or ASR) involves adding water to an underground aquifer through injection wells or infiltration galleries. If treated wastewater is used and then subsequently recovered for water supply, USR constitutes a form of reuse. The advantages of wastewater reuse through USR are twofold: it helps replenish depleted groundwater in aquifers that are overdrawn and it provides below ground storage of water which eliminates evaporative losses that would occur in a pond or reservoir. USR has received much attention in the last 20 years particularly in regions in which groundwater levels have fallen due to excessive pumping.

State regulations pertaining to USR were adopted in 2001 and are contained in 19.25.8 NMAC. Implementation of a USR project requires obtaining two state permits; a USR permit from the NMOSE and a groundwater discharge permit from the NMED. The USR permit governs the quantity of water that can be stored underground while the groundwater discharge permit regulates the quality of the injected water. There are four USR projects in New Mexico, which are summarized in Table 1. The two Rio Rancho projects use treated wastewater for USR, but at present they do not recover this water for potable or other use.

Table 1. Approved Underground Storage and Recovery (USR) permits in New Mexico (NMOSE, 2024)

Name	Recharge Type	Source of Water	Permitted Discharge (AF/yr)	Permittee
Mariposa Site, USR-1	Subsurface infiltration	Treated wastewater	336	City of Rio Rancho
Bear Canyon, USR-2	In stream surface infiltration	Untreated river water	3,000	ABCWUA
Rio Rancho Direct Injection Project, USR-3	Direct injection	Treated wastewater	1,120	City of Rio Rancho
Large Scale Aquifer Storage and Recovery, USR-4	Direct injection	Treated drinking water	4,500	ABCWUA

Intentional use of surface water to recharge an aquifer is referred to as managed aquifer recharge (MAR). There are three somewhat related technical challenges to using treated wastewater for MAR: (1) treating the water so it that does not plug the aquifer, (2) assuring that the quality of the treated wastewater is compatible with groundwater in the aquifer, and (3) assuring that recovered groundwater meets regulatory standards for subsequent reuse. Reviews of the history and technical challenges of MAR have been published by Alam et al. (2021) and by Zhang et al. (2020). The first challenge relates to the ability to introduce water from the surface to the aquifer without plugging the formation. If treated wastewater is used, it must be treated to a very high quality to remove all suspended solids and assure that microbial growth will not plug the interstitial pore space. The second challenge is to assure that the water quality meets New Mexico groundwater standards and that the chemistry of the water being introduced to the aquifer is compatible with that in the aquifer to assure that dissolution of solids in the aquifer will not affect the quality of water for later use and that minerals will not precipitate in the pore space and plug the aquifer. A third challenge, somewhat unique to New Mexico, is that the project must demonstrate that recharge water is reaching groundwater and thereby raising the groundwater head in the aquifer. Demonstrating this can be difficult in deep, semi-confined aquifers subject to large pumping from nearby wells (Miller et al., 2021a). A more detailed discussion of aquifer recharge methods is presented in the next chapter on stormwater capture.

Although there are many attractive features attributed to wastewater reuse through implementation of a USR project, the fact that there are so few in New Mexico is testimony to the difficult regulatory, technical, and economic challenges that must be met.

Water Treatment Requirements

Currently there are no federal or state regulations that specifically address either non-potable or potable water reuse. The regulatory status for NPR and DPR is summarized below.

Non-Potable Reuse: New Mexico does not have any regulations pertaining to NPR of reclaimed wastewater. However, the NMED Ground Water Quality Bureau (GWQB) has published guidance for non-potable reuse of reclaimed domestic wastewater (NMED, 2007). This guidance does not have the force of regulations, but it does identify water quality criteria and acceptable practices that should be met in order to protect health and the environment. These criteria are incorporated in groundwater discharge permits that are issued by the GWQB under regulations in 20.6.2 NMAC. The guidance document identifies four classes of reuse of reclaimed water.

- Class 1A Reclaimed Wastewater: This is the highest quality of reclaimed wastewater and can be used for most non-potable applications including irrigation of food crops provided that there is no contact between the edible portion of the crop and the wastewater. Specifically, spray irrigation of reclaimed wastewater is not recommended although it can be allowed with low trajectory spray nozzles and other restrictions.
- Class 1B Reclaimed Wastewater: This is the second highest quality of reclaimed wastewater and is suitable for uses in which public exposure is likely. Examples of acceptable uses include irrigation of parks, school yards, golf courses, urban landscaping, and street cleaning.
- Class 2 Reclaimed Wastewater: This water may be used where public access and exposure is restricted. Examples of acceptable uses include irrigation of feed crops for milk producing animals, livestock watering, irrigation of roadway median landscapes, dust control, and soil compaction.
- Class 3 Reclaimed Wastewater: This water may be used where public access and exposure is prohibited. Examples of acceptable uses include irrigation of forest trees (silviculture) and irrigation of pastures of non-milk producing animals.

The wastewater quality requirements for each class of reuse are summarized in Table 2. Additional recommendations and details on acceptable uses, wastewater application methods, access restriction and set-back requirements, water quality sampling, and measurement frequency are found in the guidance document (NMED, 2007).

The New Mexico Water Quality Act (NMSA 74-6) allows use of up to 250 gal/d of household gray water for landscape irrigation without a permit. Gray water is defined as "untreated household wastewater that has not come in contact with toilet waste and includes wastewater from bathtubs, showers, washbasins, clothes washing machines and laundry tubs, but does not include wastewater from kitchen sinks or dishwashers or laundry water from the washing of material soiled with human excreta, such as diapers (NMED, 2003)." If the flow is greater than 250 gal/d, a groundwater discharge permit is required and the reuse application must comply with the guidelines described above.

Table 2. Summary of wastewater quality requirements for each class of non-potable wastewater reuse (NMED, 2007)

		Wastewater Quality Requirements	
Class of Reclaimed Wastewater	**Wastewater Quality Parameter**	**30-day Average**	**Maximum**
Class 1A	BOD_5[1]	10 mg/L	15 mg/L
	Turbidity	3 NTU[2]	5 NTU[2]
	Fecal Coliform Bacteria	5 per 100 mL	23 per 100 mL
Class 1B	BOD_5[1]	30 mg/L	45 mg/L
	Total Suspended Solids	30 mg/L	45 mg/L
	Fecal Coliform Bacteria	100 per 100 mL	200 per 100 mL
Class 2	BOD_5[1]	30 mg/L	45 mg/L
	Total Suspended Solids	30 mg/L	45 mg/L
	Fecal Coliform Bacteria	200 per 100 mL	400 per 100 mL
Class 3	BOD_5[1]	30 mg/L	45 mg/L
	Total Suspended Solids	75 mg/L	90 mg/L
	Fecal Coliform Bacteria	1,000 per 100 mL	5,000 per 100 mL

Notes:
[1]BOD_5 is the 5-day biochemical oxygen demand
[2]NTU is nephelometric turbidity units

Non-potable reuse can be an effective use of treated wastewater; however, its suitability for urban application is problematic because it requires a completely separate pumping, storage, and distribution system. The Universal Plumbing Code requires use of purple pipes, fixtures, and valves to clearly identify the water as non-potable in order to limit the risk of cross contamination between potable and non-potable water distribution systems. A separate distribution and storage system for NPR adds cost to the project that must be factored into consideration of its feasibility.

Potable Reuse: National regulations for public water supplies are established under the Safe Drinking Water Act (SDWA). This act allows states to establish regulations that are equal to or more stringent than federal regulations. New Mexico state drinking water regulations are contained in 20.7.10 NMAC, which are adopted under authority of the Environmental Improvement Act (NMSA 74-1). State regulations adopt the federal SDWA regulations "by reference" so that state and federal regulations are the same. At present there are no federal or state regulations specifically pertaining to DPR of reclaimed wastewater (EPA, 2024).

Although there are no federal regulations governing DPR of wastewater, the SDWA allows states to establish their own regulations. California (2023) and Colorado (2023) are two of the first states to establish regulations for DPR. California spent 13 years studying the issues associated with DPR and in December 2023 became one of the first states to promulgate regulations regarding this practice (California, 2023). A 12-member expert panel was convened to assist with development of the regulations and their conclusions are summarized by Crook et al. (2022). Many of these panelists also participated in developing a framework for DPR organized by the National Water Research Institute (Tchobanoglous, et al., 2015), which provides a more comprehensive discussion of factors in implementing a DPR project including regulatory, technical, and public outreach considerations. The report also provides discussions of public health aspects, wastewater and advanced water treatment processes, residuals management, facilities operation and maintenance, and process monitoring. Recent research has specifically focused on public health outcomes of DPR to better understand this aspect (Soller et al., 2019).

Two types of risks are posed by DPR (NRC, 2012b): risks from chemical constituents and risks from pathogens. For advanced water treatment trains, most regulated chemicals are reliably removed to below SDWA standards by the treatment processes (NRC, 2012b). Furthermore, most contaminants regulated under the SDWA pose a chronic risk rather than an acute risk that only becomes problematic over long periods of exposure, typically many decades. The most familiar examples of this class of chemicals are carcinogenic compounds. Acute toxic effects for most carcinogens are not exhibited unless concentrations are orders of magnitude greater than those established to protect from chronic effects.

Concerns regarding the presence of un-regulated contaminants of emerging concern (CECs) has led to guidance for monitoring several classes of these constituents including pharmaceuticals, personal care products, food additives, and hormones (NRC 1998; Tchobanoglous et al., 2015). In addition to SDWA standards, California's DPR regulations established a total organic carbon (TOC) standard of 0.5 mg/L and the water utility must monitor for a suite of CECs (California, 2023). Sampling and analyses of these constituents is costly and must be factored into the operating costs of a DPR project.

In contrast to chemical contaminants, a wide variety of pathogenic organisms may be present in treated wastewater and these pose acute risks; one-time ingestion of even a small amount of contaminated water can lead to serious illness. These are sometimes referred to as microbial constituents of concern and they are the focus of revisions to regulations under the SDWA such as the Long Term 2 Enhanced Surface Water Treatment Rule (71 FR 654, 6/5/2006). Limiting the risk of exposure to infectious agents is one of the principal objectives of proposed and promulgated wastewater reuse regulations for both NPR and DPR.

The SDWA drinking water standards for pathogens depend on the source water. A numeric criteria of 0 organisms per 100 mL is established for *E. coli*. Additional treatment consisting of filtration and disinfection is required for systems using surface water or groundwater under the influence of surface water for heterotrophic bacteria, *Cryptosporidium* oocysts, *Giardia lamblia* cysts, *Legionella* and enteric viruses (USEPA, 2024). These organisms are more difficult to remove or inactivate than *E. coli* by conventional treatment processes so that requiring additional treatment adds conservatism to drinking water standards.

Because the concentrations of pathogenic organisms in wastewater can be much higher than in surface or groundwater and because it is difficult to monitor these organisms, DPR criteria are instead based on the use of a sequence of treatment technologies that can provide reduction of these pathogens by many orders of magnitude. This is measured as logarithmic reduction values (LRV) defined as:

$$LRV = \log_{10} \frac{C_{inf}}{C_{eff}}$$

where C_{inf} is the pathogen concentration in the influent and C_{eff} is its concentration in the treated effluent. Thus, 1 LRV corresponds to 90% pathogen removal, 2 LRV corresponds to 99% removal, 3 LRV corresponds to 99.9% removal and so on. The DPR standards for California (2023) and Colorado (2023) both require LRVs as summarized in Table 3. The California standards are based on DPR posing an annual risk of infection to the public of 10^{-4} (i.e., one infection each year caused by ingestion of recycled wastewater in a population of 10,000 people). A discussion of the science underlying these regulations has been published by Gerrity et al. (2023).

Table 3. Assumed concentration of regulated pathogens in raw wastewater and Log Reduction Values (LRV) required by treatment trains for Direct Potable Reuse (DPR) in California and Colorado (California, 2023; Colorado, 2023)

		Log Reduction Values (LRVs)	
Constituent	**Concentration in Raw Wastewater (No./L)**	**California**	**Colorado**
Enteric virus	10^5	20	12
Giardia lamblia cysts	10^5	14	10
Cryptosporidium oocysts`	10^4	15	10

The LRV values in California for IPR projects are the same as for those for DPR projects in Colorado (12, 10, and 10). The LRVs established for DPR projects in California and Colorado are based on the entire treatment system between the untreated wastewater influent and the effluent treated drinking water. Texas DPR regulations require LRVs of 8.0, 6.0, and 5.5 for enteric virus particles, *Giardia lamblia* cysts, and *Cryptosporidium* oocysts respectively; however, these values are for the advanced potable water treatment system only and are based on a drinking water plant influent consisting of highly treated wastewater instead of raw sewage (TCEQ, 2022). Direct Potable Reuse regulations in Colorado establish the same LRV values if the influent is highly treated wastewater (Colorado, 2023).

The LRVs for each unit operation in a treatment train must be approved by state regulators. Arden et al. (2024) published the results of an extensive literature review of LRVs for 31-unit processes used in reuse projects and found wide variation in reported values for common water treatment unit operations. The reported LRVs for common drinking water treatment processes are summarized in Table 4 based on the literature review by Arden et al. (2024). This review compiled over 1100 individual LRVs. The wide range in reported values is due to variations in the design of the different process, the operations and maintenance procedures used by the plant, differences in the organisms measured (i.e., difference between the protozoans *Giardia lamblia* and *Cryptosporidium*), and the quality of the water fed to each process. The variability illustrates the importance of considering the entire treatment train when assigning log reduction credits for a proposed DPR project.

Table 4. Reported Log Reduction Values (LRVs) for selected water treatment processes for virus particles, bacteria, and protozoa (Arden et al., 2024)

	Reported Log Reduction Values		
Process	**Virus**	**Bacteria**	**Protozoa**
UV Disinfection	-0.4 – 5.8	-0.3 – 8.3	0.1 – 3.4
UV + H_2O_2 Disinfection	0.9 - 4	0.4 – 5	0.7 – 2.2
Chlorination	-0.4 – 6.5	0.3 – 8	0.4 – 0.7
Ozonation	0.2 – 5.6	0.3 – 4	2 – 2
Microfiltration or Ultrafiltration	0.3 – 5.8	1.5 – 7.5	ND[1]
Reverse Osmosis and Nanofiltration	2.4 – 3.9	0 – 1.9	ND[1]

Notes:
[1]No Data

Example – Cloudcroft, New Mexico

The Village of Cloudcroft is located at an elevation of 8,700 ft in the Sacramento Mountains of southern New Mexico. The village has a population of about 750 residents but during the tourist season it can swell to over 3,000 people. The village relies upon shallow wells part way down the mountain as its source of water; however, this supply is insufficient to meet peak demand during summer months. Furthermore, since it is located near the crest of the mountains, hydrogeological investigations have concluded that there are no alternative sources. The Village does not receive return flow credits for its wastewater discharge so it began investigating a DPR project to meet their water demands in 2002.

The Village was able to obtain multiple sources of external funds to design and build a state-of-the-art DPR system referred to as the "PURe Water Project." When it was designed in the early 2000s, the PURe plant would have been the first DPR in the U.S. A flow diagram of the system is presented in Figure 3. The treatment train consisted of the following.

- Membrane bioreactor (MBR) to provide advanced wastewater treatment
- Reverse osmosis (RO) to remove inorganic and organic constituents
- Ultraviolet based advanced oxidation process (UV-AOP) to provide enhanced disinfection and remove recalcitrant organic compounds
- Chlorination to provide a residual disinfectant concentration to prevent microbial growth of the treated water during storage
- Ultrafiltration (UF) to provide further removal of particulates including virus particles, bacteria, and protozoans
- Low-dose ultraviolet (UV) disinfection to provide additional disinfection
- Granular activated carbon (GAC) adsorption to remove residual organic compounds including CECs
- Final chlorination and storage to provide a residual disinfectant concentration to prevent microbial growth during storage and distribution

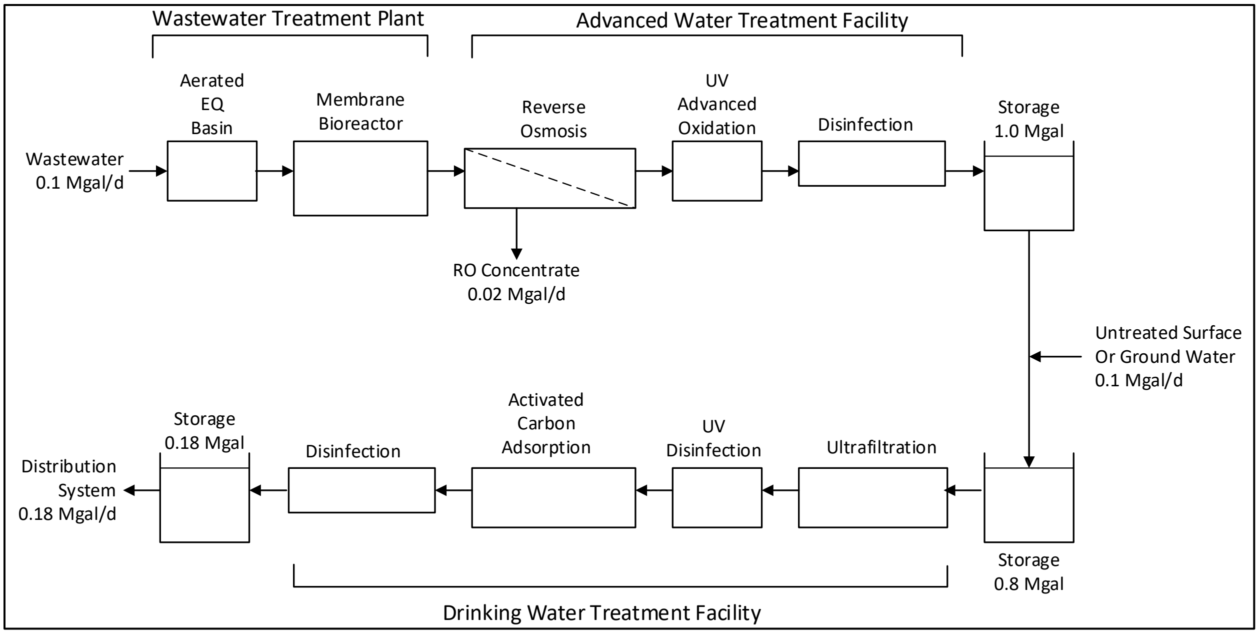

Figure 3. Schematic of the PURe water treatment process (Crook et al., 2015). (Mgal/d refers to million gallons per day).

Construction of the system was essentially completed in 2009; however, except for the membrane bioreactor for wastewater treatment, the advanced water treatment facility has not been operated to date in part because the community did not have sufficient resources to pay for its operation and maintenance, and in part because it did not receive necessary approval from NMED. A recent preliminary engineering report concluded that completing and operating the PURe Water project would not be cost effective and recommended an aggressive leak detection and prevention program to reduce water losses in order to meet future needs (CDM Smith, 2024).

Because New Mexico does not have regulations governing DPR and because the Cloudcroft system was one of the first DPR projects in the country, the NMED contracted with the National Water Research Institute (NWRI) to conduct a review of the project, identify operation and maintenance needs, identify sampling and analysis needs, and recommend whether the project was sufficiently protective of human health that it could be operated as a DPR project (Crook et al., 2015).

The NWRI review panel noted that pathogens present acute risks whereas chemical constituents present chronic risks. Therefore, pathogens that might not be removed in the event of a failure of one of the treatment processes would be the greatest risk to consumers and constitute the most significant design and operating concerns for the Village's DPR system (Crook et al., 2015). The review panel did not explicitly identify a required log reduction value for the PURe water system, but based on LRV values cited in its report, the panel found that the overall process would provide over 17 LRVs for enteric virus particles, 21 LRVs for *Giardia lamblia* and 18 LRVs for *Cryptosporidium oocysts*. This exceeds the LRVs for the same organisms established in the Colorado regulations and exceeds the requirements in the California regulations except for enteric virus particles (Table 3). The degree of conservatism in the PURe water process design was the result of treatment requirements imposed on the project by NMED staff in light of uncertainty about the risks posed by DPR during initial development of the conceptual design for the Cloudcroft system.

In addition to wastewater and water treatment systems needed for a successful DPR project, the NWRI review identified five other areas that must be addressed in order to successfully implement a DPR project (Crook et al., 2015). They include the following.

- Operations and maintenance: O&M of a DPR treatment system is challenging because of its use of a sequence of complex processes. Plant personnel require advanced knowledge of technologies that are not the subject of conventional water and wastewater training curricula for licensed treatment plant operators. The challenge of finding and paying for highly qualified operators is especially problematic in small, remote communities with limited financial resources.
- Process control and monitoring: It is important to document plant performance to be able to identify and remedy failures of unit operations. Monitoring of plant performance, and especially removal of high-profile CECs, is important to maintain regulatory and public acceptance of the system.
- Source control: Some contaminants found in municipal wastewater are difficult to remove by conventional treatment processes. A more effective strategy is to prevent the introduction of these contaminants to the wastewater collection system through a pretreatment program that limits introduction of contaminants at their source. Small communities generally do not have effective pretreatment programs for the contaminants of concern, though they may receive industrial or other problematic wastes that would be most effectively managed at the source rather than treated at the wastewater treatment plant.
- Financial implications: The NWRI report recognizes that the facilities for a DPR system and their operation, maintenance, and monitoring are much more expensive than for conventional wastewater and water treatment. The report emphasized the importance of maintaining an asset management plan to maintain an inventory of all physical infrastructure in the system, its level of service, its lifecycle cost and to develop a funding strategy for paying for repair, rehabilitation, and replacement of these assets.
- Public acceptance and outreach: The community must establish a proactive, transparent, and consistent outreach program early in the planning process for the DPR project to gain public support for the project.

Conclusions

The following conclusions can be made from this discussion of wastewater reuse.

- Wastewater reuse does not on its own reduce a community’s consumptive use of water. Thus, either non-potable or potable reuse may impact the community’s water rights if it receives return flow credits by decreasing its discharge of treated wastewater. If the community does not receive return flow credits or have downstream obligations for its effluent, wastewater reuse may constitute an attractive source of water for augmenting its water supply.
- The circumstances under which wastewater reuse may be a source of supplementing a community’s water supply include:

    - If the community has or is able to obtain surface water rights to offset reductions in wastewater discharge
    - If the community has the financial and technical resources to build and operate a wastewater reuse system
    - If the community is able to obtain public acceptance of a reuse system
- New Mexico does not have regulations governing any type of wastewater reuse including NPR, IPR, or DPR. The NMED has published guidelines that identify water quality that is appropriate for different NPR uses. These uses range from irrigation of food crops, parks, golf courses, and school yards to irrigation of non-food crops for farm animals.
- There are no federal or New Mexico regulations governing IPR or DPR. Regulations in other states recognize that the greatest health risks posed by DPR are the acute risks posed by pathogenic microorganisms in wastewater. Risks are limited by requiring use of a sequence of water treatment unit operations that achieve log reduction values (LRVs) for enteric viruses and the protozoans *Giardia lamblia* and *Cryptosporidium oocysts*.
- Use of treated wastewater for urban NPR requires a separate pumping, distribution, and storage system that adds considerable cost and complexity to the project. It also increases the risk posed by cross contamination between the non-potable and the potable water distribution and storage system.
- Treated wastewater may be discharged to an aquifer as part of an IPR system where the aquifer will constitute an environmental buffer to provide additional water quality protection prior to its being withdrawn for potable use
- Wastewater reuse for underground storage and recovery (USR) offers the advantage of replenishing groundwater supplies and provides storage with no evaporation losses. However, USR projects require that the treated wastewater meet stringent New Mexico groundwater standards. For most constituents, these criteria are similar to drinking water standards The chemistry of the treated wastewater must also be compatible with groundwater chemistry to prevent interactions between the two that may damage the aquifer or compromise the quality of the stored water. Only four USR projects have been approved in New Mexico and only two of these, both operated by the ABCWUA, currently recover stored groundwater.
- Treatment systems to meet the new regulations require the use of complicated, state-of-the-art unit operations that in turn must be operated by highly skilled operations personnel. Additional costs will be incurred by the need to provide frequent monitoring for a host of regulated and un-regulated constituents.
- In planning for a DPR project, the community must consider a number of factors in addition to the degree of treatment provided. These include: the cost and availability of qualified O&M personnel; provision of a source control program to limit introduction of toxic and hazardous compounds into the distribution system; the affordability of the project including capital, O&M, and replacement costs as identified in an asset management program; and public acceptability of the DPR concept.

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Stormwater Capture and Reuse

Introduction

Stormwater capture and subsequent use of the water has considerable appeal nationally and especially in arid regions due largely to three common assumptions. First, stormwater is highly visible; every time it rains water flows down the streets, into storm drains and subsequently into arroyos, streams, and rivers and appears to be water that is wasted. Second, it is easy to imagine methods of capturing and using stormwater: simply collect it in ponds and reservoirs, provide appropriate treatment, and use it for potable or non-potable purposes. Finally, to those unfamiliar with New Mexico water law, stormwater does not have an obvious owner and therefore appears to be water that is there for the taking. Recent discussions of stormwater capture and reuse have been provided by Berhanu et al. (2024), Begum et al. (2008), Hoffman (2008), Jefferson et al. (2017), Luthy et al. (2019), Madison and Emond (2008), Porse and Pincetl (2019), Singh et al. (2023), and Smith et al. (2022). While California has established policies that encourage stormwater capture and reuse (CWB, 2016), other southwestern states have been slower to consider this possible resource.

Based on the perception that stormwater represents a significant source of new water for supplementing current supplies, stormwater capture is frequently identified as a popular alternative source among both public and professional water managers. For example, Albuquerque residents ranked stormwater capture as the second highest of ten alternatives considered for augmenting future public water supplies in a community-wide public engagement process (ABCWUA, 2019). The New Mexico Water Policy and Infrastructure Task Force (2022) recommended stormwater capture for augmenting supplies. The state's 50-Year Water Action Plan (Grisham, 2024) calls for improved stormwater infrastructure to increase groundwater recharge and create greater opportunities for water reuse.

Despite this enthusiasm for stormwater capture and reuse, there has been little formal consideration of the constraints and challenges associated with this concept. In the case of the Albuquerque alternatives, utility managers listed the advantages of stormwater capture but gave no information on the costs, complexities, or consequences of such a strategy (ABCWUA, 2019).

It is suggested that there are five major challenges to stormwater capture and use that must be recognized when considering development of this potential resource.

- Regulatory challenges, especially water rights and downstream delivery requirements
- Hydrologic challenges associated with the nature of storms and stormwater flows in arid environments
- Engineering and infrastructure challenges associated with capturing, storing, treating, and transporting stormwater to potential users
- Water quality challenges due to high sediment loads and highly contaminated runoff from urban watersheds
- The capital and operating costs of building the infrastructure and subsequently operating and maintaining a stormwater capture, storage, treatment, and distribution system

The first four considerations affect the costs of a stormwater capture project that will be specific to each individual project. Therefore, this discussion focuses on the first four constraints to describe the non-economic factors that affect the feasibility of a stormwater capture project in an arid climate. The intent is to identify and discuss the types of issues that must be addressed when considering stormwater as a source for augmenting a community or region's water supply. This discussion is presented using examples of issues in the Middle Rio Grande watershed of central New Mexico.

Note that the focus of this paper is on stormwater capture projects at the community or regional scale. It does not address green stormwater infrastructure or low impact development (GSI-LID) strategies such as on-site rainwater harvesting, roadside bio-swales, or diverting overland runoff to irrigate roadside vegetation (Wonmin et al., 2014). Some of these strategies are incorporated in the City of Albuquerque's Development Process Manual (CABQ, 2019). The New Mexico Office of the State Engineer (NMOSE) also offers guidance on rainwater harvesting though it is limited to small projects such as rooftops, commercial sites, and parks (NMOSE, 2025).

Regulatory Challenges

The New Mexico state constitution, adopted in 1911, states that "all water of every stream, perennial or torrential, within the state of New Mexico is hereby declared to belong to the public and to be subject to appropriation for beneficial use" (Article XVI, Section 2, Toulouse Oliver, 2019). This section also states that the right to use water (i.e., a water right) is granted based on the principle of prior appropriation in which the most senior right has precedence over junior rights. Water rights are administered by the NMOSE. A summary of water law and administration in New Mexico has been published by the Utton Transboundary Resources Center (Utton Center, 2016).

Stormwater capture is addressed in state law that states that "the water shall not be detained in the impoundment in excess of 96 hours unless the state engineer has issued a waiver to the owner of the impoundment (NMAC 19.26.2.15.B)." This allows an entity to detain stormwater for the purposes of attenuating a flood wave, but all of the water must be released within 96 hours unless the water can be diverted, stored, and used by obtaining a water right." This is the famous (or infamous depending on one's perspective) "96 hour rule."

Regulations affecting stormwater capture in other southwestern states vary widely. The California State Water Board has adopted policies that encourage stormwater capture and set a goal of capturing 1,000,000 AF/yr ($1.2x10^9$ m^3/yr) by 2030 (Shimabuku et al., 2018). But California is a downstream state with only one compact dealing with interstate flow of water (the California-Nevada Interstate Compact); thus, downstream and return flow issues are generally of little concern. Indeed, many of the communities in California with the greatest need for additional water supply are on the coast with no downstream users of surface water, hence there are no water rights constraints limiting capture and reuse if urban runoff. Thus, much of the literature on stormwater capture and reuse is based on conditions and criteria in California. One of the more comprehensive discussions of the resource and technical challenges associated with its use is by Luthy et al. (2019), which discussed stormwater capture options with special attention given to Los Angeles, a water-short community with no downstream communities, rivers, or return flow requirements.

Colorado, Nevada, and Utah have stringent regulations affecting stormwater retention and detention. Utah allows collection of rooftop runoff but the volume is limited to 200 gallons in covered containers without a permit, or up to 2,500 gallons in a registered retention facility (UTDWR, 2010). However, stormwater collection and use are limited to the same parcel of land on which water is captured and stored. Similarly, until 2015 all stormwater capture in Colorado was prohibited. Legislation passed in 2015 allowed on-site capture but limits it to 110 gallons of rooftop runoff. Community and regional-scale stormwater detention facilities must release 99% of stored water within 120 hours (CODWR, 2016). Nevada limits stormwater collection to rooftop runoff from single family dwellings (NVLCB, 2019). New Mexico does not limit the volume of water that can be captured by rooftop rainwater harvesting but does not allow capture and reuse of runoff once it leaves the owner's property.

The 96-hour rule brings to light a subtle but important distinction between two terms used in arid region stormwater management, namely, retention and detention. Retention refers to capturing and retaining runoff indefinitely whereas detention refers to capturing then releasing all stormwater within a short period. In New Mexico, retaining water for later use requires a water right. Detention requires releasing the water within 96 hours; detaining it longer than 96 hours requires a water right.

Virtually all urban stormwater ponds and reservoirs in New Mexico must comply with the 96-hour rule. Therefore, stormwater detention ponds are not designed to hold a permanent pool of water, and accordingly, stormwater dams are referred to as "dry dams." This has important consequences on dam design, construction, and operation as well as potential use of these ponds and reservoirs for stormwater capture and storage, which will be discussed later.

In addition to state law, New Mexico is party to eight interstate stream compacts (NMISC, 2024), which are federally approved agreements between states that govern the sharing of water in rivers or streams that flow across state boundaries. Discussions of the role of compacts in administering western water resources have been provided by Muys et al. (2007) and Schlager and Heikkila (2009). Compliance with compacts is delegated to the Interstate Stream Commission (ISC) (NMISC, 2024). One of the major responsibilities of the ISC is to assure delivery of water to downstream states according to provisions established in each compact. As stormwater is an important component of stream and river flows, the ISC works with the NMOSE to ensure that stormwater capture does not impair downstream water deliveries.

When Might Community-Scale Stormwater Capture Be Legally Feasible

It is clear from this discussion that the regulatory challenges of stormwater capture and use in New Mexico are substantial. If there are no clearly identified downstream water users, there are some circumstances where runoff capture may be allowed.

The first scenario might be in hydrologically closed basins that do not have surface water drainage from them. Notable closed basins in New Mexico include the Estancia Basin, Tularosa Basin, and the Mimbres Basin. In addition, there are no return flow constraints on runoff in communities on the eastern plains that discharge to playa lakes. However, in a closed basin, objections to stormwater capture might be raised if it reduces the water supply for other users in the basin.

The second circumstance where stormwater capture might be allowed is in basins that are not subject to interstate stream compacts such as the Texas Gulf basin of far southeastern New Mexico. There are no perennial streams or surface water supplies in this region, hence downstream communities would not be affected by stormwater retention.

A third example where hydrologic circumstances are favorable to stormwater capture and reuse might be on the lower Rio Grande below Elephant Butte Reservoir. The outlet at Elephant Butte Dam is the delivery point for water to the lower Rio Grande and Texas under the Rio Grande Compact. Capturing runoff below this delivery point would historically have no effect on compact compliance, hence stormwater capture and reuse is not constrained by regulatory issues. Ongoing U.S. Supreme Court litigation in Texas v. New Mexico may complicate water delivery issues in the Lower Rio Grande (U.S. Supreme Court, 2020).

Sidebar Discussion – Green-On-Green Conflict

State prohibition against retaining stormwater in New Mexico led to a noteworthy conflict between state water law and the federal Clean Water Act (CWA). New Mexico is one of three states that does not have primacy for administering the National Pollutant Discharge Elimination System (NPDES) permit program under the CWA; this program is administered by EPA Region VI in Dallas. In 2014, EPA proposed a regional stormwater discharge permit for the urban area surrounding Albuquerque that required retention of runoff from the two-year precipitation event (i.e., the 90% storm) (USEPA, 2014). This requirement is inconsistent with the state's 96-hour rule; accordingly, the Director of the New Mexico Interstate Stream Commission wrote a letter protesting this requirement (Dunlap, 2015). This is a classic example of the green-on-green conflict in which one regulatory program meant to protect the environment conflicts with another. In response, EPA modified the NPDES permit to clarify that in the event of a conflict over stormwater retention, state water law would hold priority.

Hydrologic Challenges

The hydrology of the arid southwest consists of long dry periods with no precipitation punctuated by short but very intense storms. In most of New Mexico, roughly half of the annual precipitation occurs in the form of thunderstorms associated with the late summer monsoon, and yet most of the flow in the three major rivers of the state (Rio Grande, Pecos, and San Juan) is due to spring snowmelt. The discussion of the challenges of stormwater capture and reuse presented here is primarily focused on the stormwater hydrology of urban Albuquerque because: (1) it is the largest urban watershed in New Mexico, (2) there are over 22 large stormwater dams that conceivably could be used for stormwater capture and reuse, and most importantly, (3) there is a large channel, the North Diversion Channel (NDC), that has a flow gage and more than 50 years of flow data; it may be the only large urban stormwater channel with a stream gage in the southwest. The large variability of monsoonal precipitation and total annual precipitation in Albuquerque is shown in Figure 4.

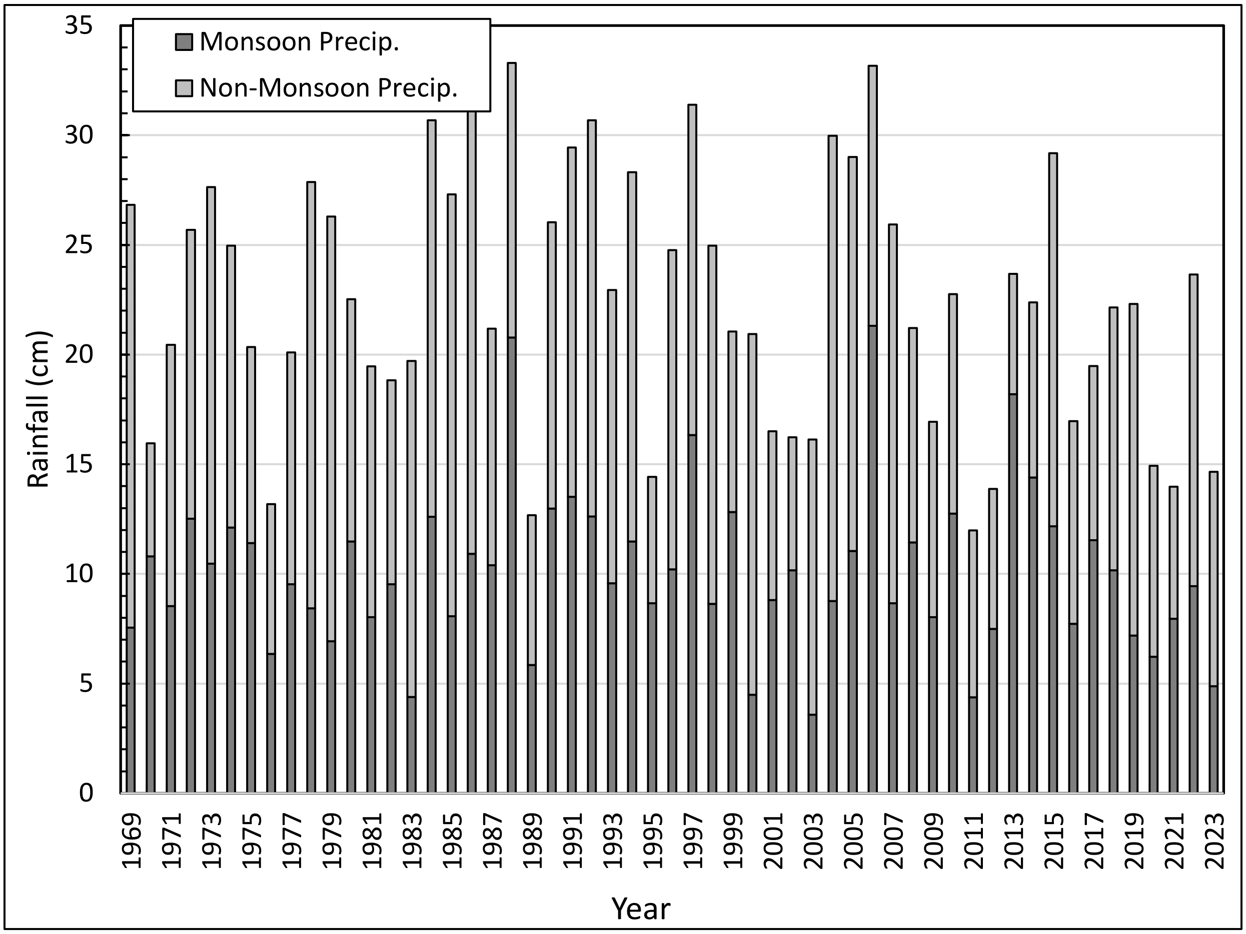

Figure 4. Total annual rainfall and rainfall in cm occurring during monsoon months of July, August and September as measured at the Albuquerque International Airport (National Weather Service data (WRCC, 2025)).

A plot of the average monthly flow in the Rio Grande at the Central Avenue gage in Albuquerque shows that the flow in the river is dominated by snowmelt from the mountains in northern New Mexico and southern Colorado; monsoon rains contribute little to the total annual flow (Figure 5). This gage is downstream from the discharge points of several large arroyos that drain urban watersheds in Bernalillo and Sandoval Counties. East of the river, the North Diversion Channel (NDC) drains 88 square miles of northeast Albuquerque including the western face of the Sandia Mountains, and is one of the few gaged stormwater channels in the southwest, discharging to the river upstream from the Central Avenue gage. On the west side of the river, three large arroyos contribute urban runoff upstream from the Central Avenue gage (the Calabacillas, San Antonio, and the West I-40 Diversion). These arroyos drain approximately 145 square miles of which about 30% is fully developed. The average flow in the Rio Grande at the Central Avenue gage shows no increase in river flow during the monsoon season illustrating that urban monsoon runoff has little influence on monthly average river flow (Figure 5).

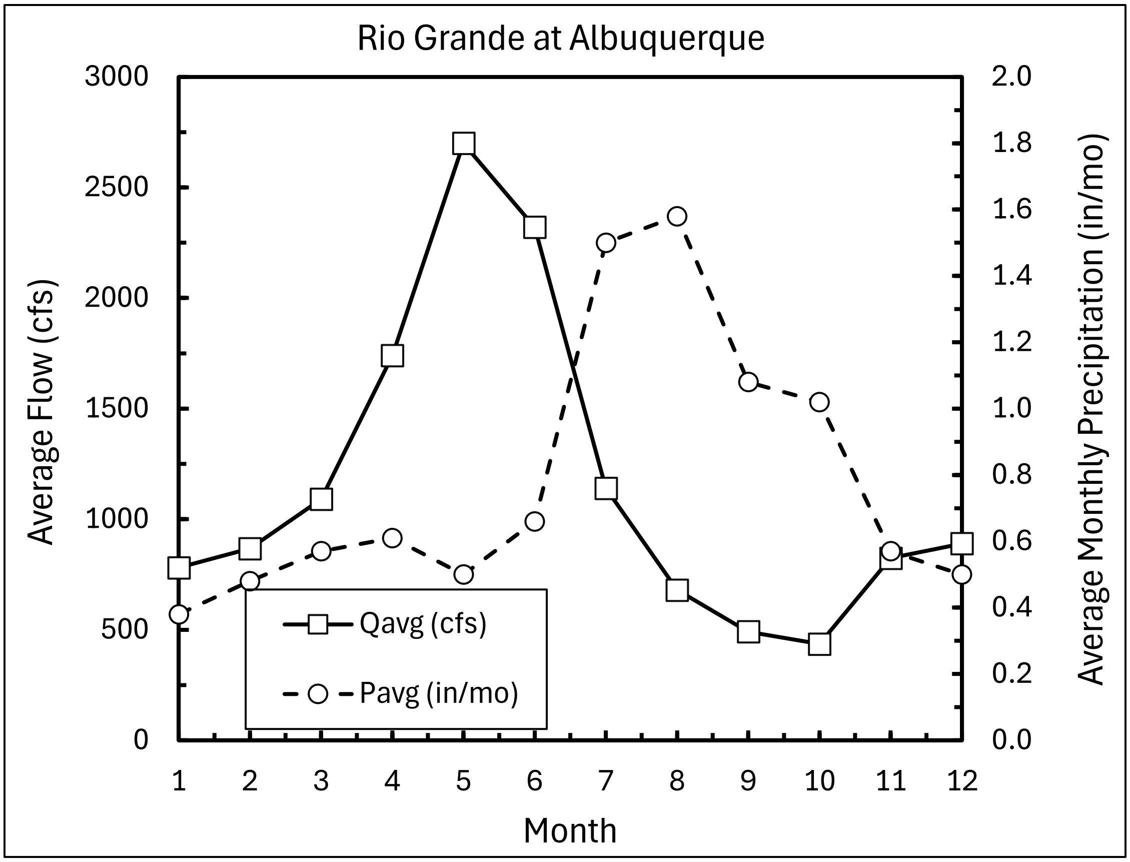

Figure 5. Plot of average precipitation and Rio Grande flows at Central Avenue in Albuquerque, New Mexico showing negligible impact of urban runoff on river flow during summer monsoon. Data from USGS (2020). (cfs means cubic feet per second).

The NDC in Albuquerque is a large concrete lined trapezoidal channel with a capacity of 44,000 cfs (1,250 m^3/s) that collects stormwater from eight large arroyos that drain nearly 88 mi^2 (228 km^2) of land in the northeast quadrant of the city including the western face of the Sandia Mountains (Figure 6). It is the only large arroyo in New Mexico, west Texas, or Arizona draining an urban watershed that has a USGS stream gage, and therefore it provides valuable information for understanding the characteristics of southwestern urban hydrology. The NDC is also relevant to the discussion of stormwater capture as it passes less than 1 km from the San Juan-Chama Drinking Water Treatment Plant at its closest point, a 90 Mgd (340,000 m^3/d) plant that diverts and treats Rio Grande water and provides roughly 75% of urban Albuquerque's potable water supply. The proximity of the NDC to this plant has led water managers to consider diverting stormwater to supplement the community's potable water supply.

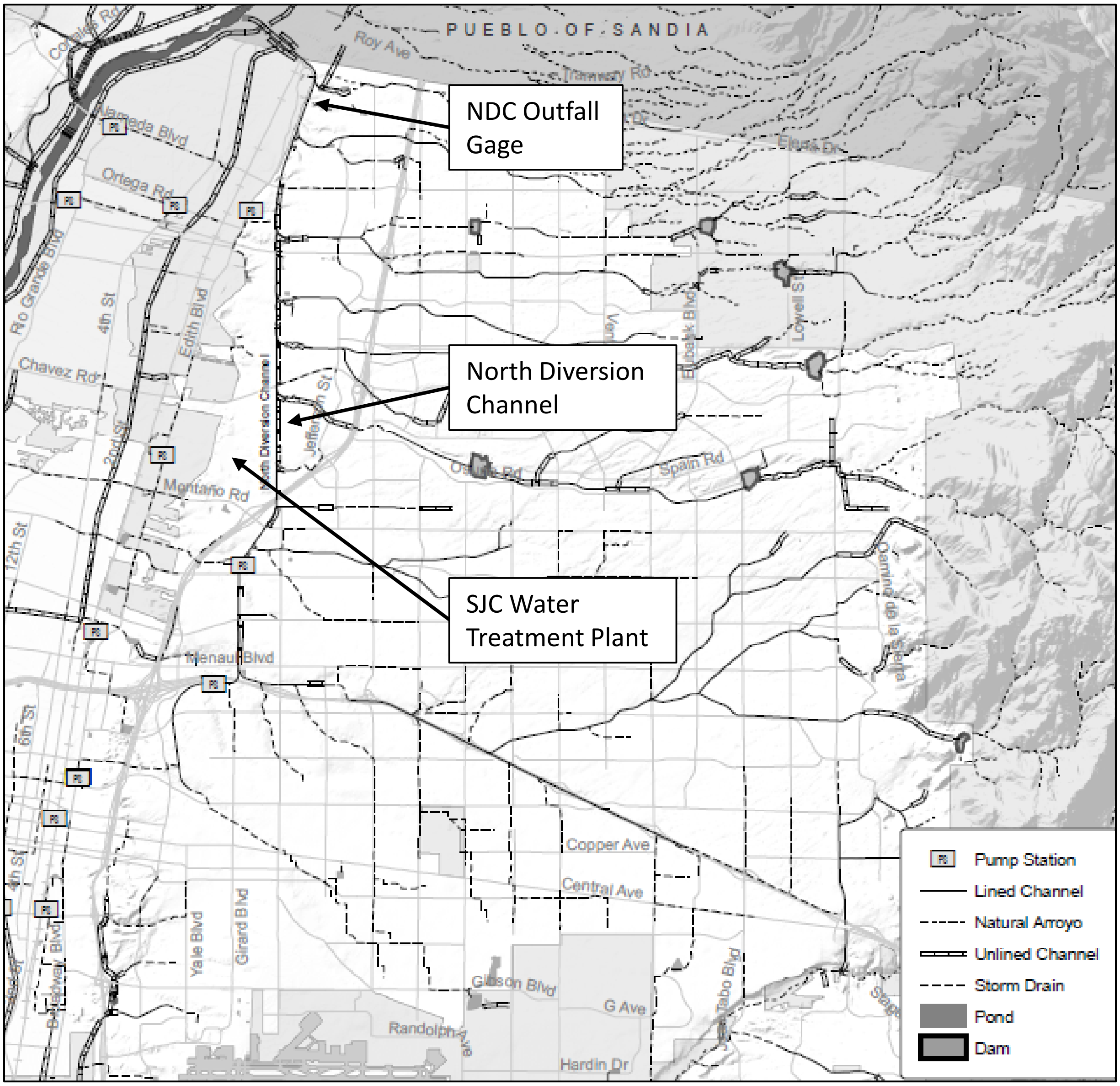

Figure 6. Map of northeastern Albuquerque showing the surface drainage system, the North Diversion Channel (NDC) and the locations of the USGS stream gage and the San Juan-Chama (SJC) Drinking Water Treatment Plant.

The NDC has a stream gage near its discharge to the Rio Grande that provides almost 60 years of data that can be used to illustrate the hydrologic challenges associated with stormwater capture. Over the period 1999 to 2016 (there is considerable missing data prior to 1999 and subsequent to 2016), total average annual outflow from the channel was 6,500 AF/yr (8.0×10^6 m^3/yr) and ranged between 10,900 AF/yr (13.4×10^6 m^3/yr) and 3,700 AF/yr (4.6×10^6 m3/yr). Flows during monsoon months average 2,900 AF/yr (3.6×10^6 m^3/yr) and range between 8,300 AF/yr (10.2×10^6 m^3/yr) and 900 AF/yr (1.1×10^6 m^3/yr). Note that the NDC passes near the drinking water treatment plant at approximately its mid-point. Therefore, although this location would be most convenient for a diversion, the amount of water available would be roughly half of the total flow measured by the gage.

Storm hydrographs for the NDC illustrate the hydrologic and hydraulic challenges of capturing stormwater from southwestern urban watersheds. The annual hydrographs for flow in the NDC during the monsoon months in 2017 and 2018 are shown in Figure 7. These years were selected as being representative of flows during years with near average monsoon month precipitation of 11.4 cm (4.54 in) and 10.2 cm (4.00 in) for 2017 and 2018, respectively, compared to a 50-year average of 10.3 cm (4.06 in) for the same months (WRCC, 2024).

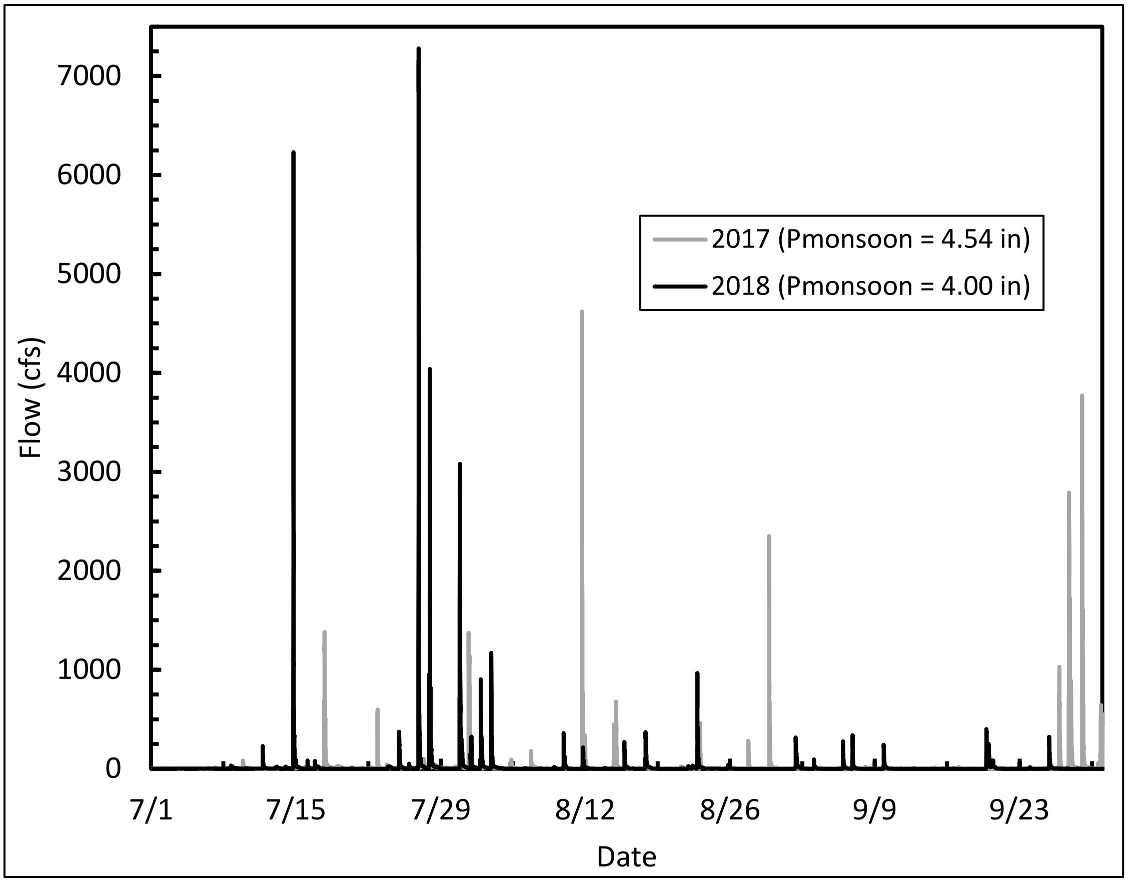

Figure 7. Stormwater hydrographs during the monsoon months of July 1 through September 30 from the North Diversion Channel for 2017 and 2018 (data from USGS, 2020). (Pmonsoon refers to total precipitation during the monsoon months of July through September).

Consider the runoff for the storms shown in Figure 7. Storms producing peak flows greater than 2,000 cfs (55 m^3/s) generally occur two to five times per year. The storm of July 26, 2018 produced a peak flow of 7,380 cfs (206 m^3/s), the highest flow in more than five years. The storm of August 11, 2017 is more representative of a typical maximum summer precipitation event with a peak flow of 4,300 cfs (122 m^3/s) (Figure 8). From a stormwater capture perspective, the very sharp and short duration hydrograph illustrates one of the engineering challenges of collecting this water for subsequent use: how to capture the runoff? In the vernacular of the southwest, they are referred to as "flash floods." During the August 11, 2017 storm, flows increased from 0 to 4,300 cfs in less than one hour and then dropped back to near 0 cfs within six hours. Twenty-four-hour rainfall measurements in the watershed averaged about

0.9 in (2.3 cm) for this storm and ranged from less than 0.5 in (1.3 cm) to greater than 1.6 in (4.1 cm) (CoCoRaHS, 2020).

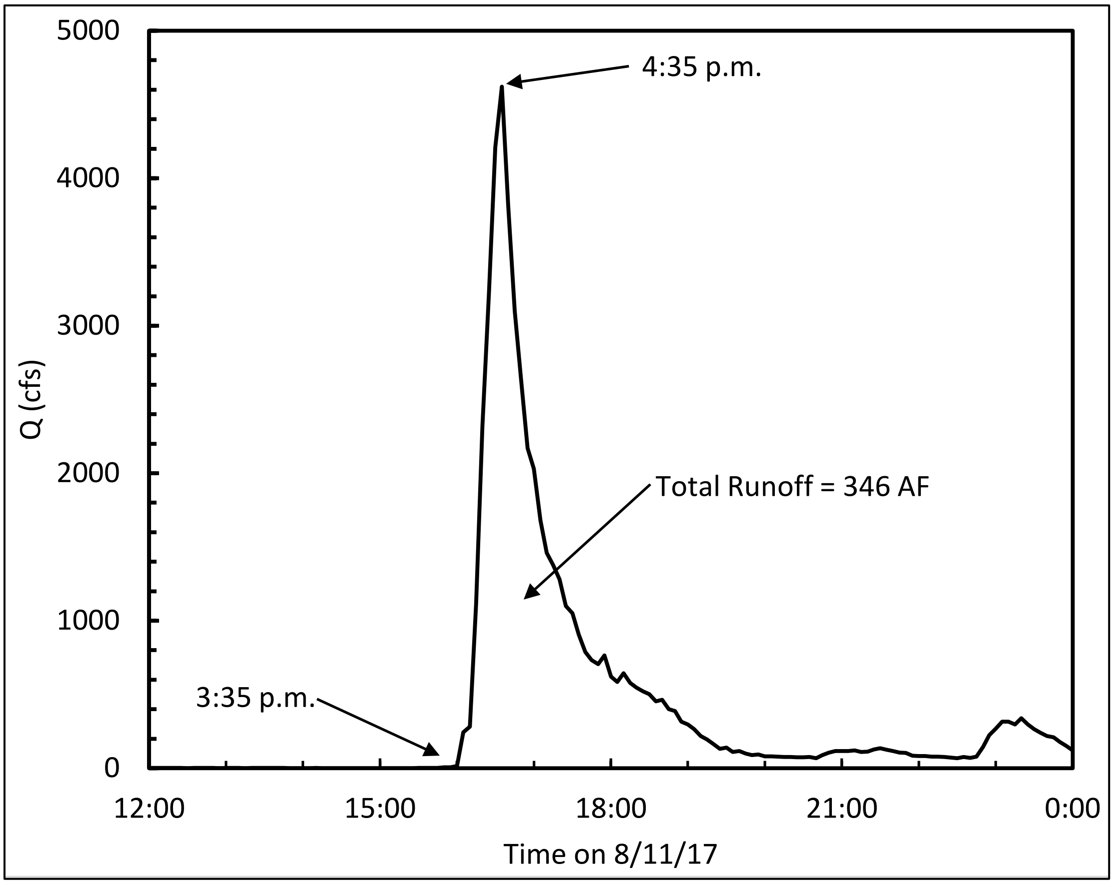

Figure 8. Hydrograph of flows in North Diversion Channel for storm occurring on August 11, 2017 (data from USGS, 2020).

The total volume of runoff from the August 11, 2017 storm was 346 AF (427,000 m^3), which should be placed in context of the region's water resources and demand. The average annual volume of water in the Rio Grande flowing past Albuquerque is 950 KAF/yr ($1.2x10^9$ m^3/yr), though it is highly variable and 10% of the time the total annual flow is less than 400 KAF/yr ($0.5x10^9$ m^3/yr) (Thomson, 2012). The total consumptive water use for customers of the local water utility is 40 KAF/yr ($50x10^6$ m^3/yr) (ABCWUA, 2019). The total annual average stormwater runoff in the 100-mile-long middle reach of the Rio Grande between Cochiti Dam and Socorro has been estimated at 20 KAF/yr ($25x10^6$ m^3/yr), while that from the NDC is 6.5 KAF/yr ($8.0x10^6$ m^3/yr), of which about half, 3.0 KAF/yr ($3.7x10^6$ m^3/yr), occurs during the summer monsoon months (Thomson, 2012). These statistics illustrate the point that though it seems like a large volume when it is racing down an arroyo, urban stormwater runoff constitutes a small fraction of the total supply of water in the Middle Rio Grande Basin. This is consistent with the absence of an increase in average monthly flows during the monsoon season shown in Figure 5. Furthermore, the sharpness of the storm hydrographs illustrates the engineering challenge of how to capture a large volume of water that runs off the watershed over a very short period of time.

Engineering and Infrastructure Challenges

In order to use urban runoff, a utility must address the complicated, large, and expensive challenges of providing the physical infrastructure needed to capture, store, possibly treat, and then transport the stormwater to its point of use. The hydrologic characteristics of an arid watershed described previously introduce enormous complexities. This is illustrated by the stormwater management in Albuquerque, where urban runoff infrastructure is managed by the City of Albuquerque, Bernalillo County, and a regional flood control authority (Albuquerque Metropolitan Arroyo Flood Control Authority, AMAFCA) (Thomson, 2021). Together these agencies operate a system of storm drains, arroyos, and more than 50 flood control ponds and reservoirs. The total storage capacity of these ponds and reservoirs is about 7 KAF (8.6×10^6 m^3). However, this number is somewhat misleading as one reservoir is an 18-hole municipal golf course that has 1.1 KAF (1.4×10^6 m^3) capacity while the capacity of most other ponds is less than 50 AF (62,000 m^3). Furthermore, all but one of the stormwater reservoirs and ponds in the Middle Rio Grande Basin are created by ungated dry dams that drain within 96 hours.

The discussion of stormwater management in Albuquerque brings to light three difficult challenges that must be met for an urban stormwater capture project to be feasible. These are summarized below.

Increased Storage Capacity

First, although large and expensive stormwater management infrastructure currently exists in most large communities in New Mexico, it was designed solely for flood protection, not water storage. In order to modify existing ponds and reservoirs for stormwater capture, additional storage capacity must be provided, either by constructing new reservoirs or modifying and raising existing dams to increase reservoir capacity. Yet all land surrounding existing ponds and reservoirs in most metropolitan area is fully developed or protected as parks or open space. Therefore, increasing the volume of existing reservoirs or constructing new ones would require acquisition of developed land that would be very costly and politically challenging. The challenge of increasing reservoir capacity to allow stormwater storage is faced in virtually all urban areas in New Mexico and beyond.

Dam Design

In New Mexico, virtually all stormwater is impounded in ponds and reservoirs behind dry dams (dams not designed to retain a permanent pool of water). There are two important characteristics of these dams. First, all but a few are ungated and designed to release all water from a full reservoir in 96 hours. Therefore, there is no way to control releases and retain water for future use. In order to use these facilities for stormwater capture and storage, the outlet works would need to be replaced with control structures. Second, and more importantly, dry dams are not designed to retain water. As soil becomes saturated, it loses its strength and threatens the integrity of earth dams and embankments (Duncan et al., 2014). For this reason, earthen structures intended to retain water are designed with an impervious core, erosion protection to protect the upstream and downstream faces of the dam, and other features to ensure their integrity. Figure 9 is a schematic of a 65-ft tall (20 m) earthen dry dam designed for stormwater detention in northeastern Albuquerque, the John B. Robert dam owned by the Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA), which has a capacity of 659 AF

(813,000 m^3). Major modifications that would be needed for this dam to include stormwater storage in its function are illustrated in Figure 10. A redesigned dam to retain a permanent pool of water would require increasing the height of the dam, adding an outlet control structure (i.e., a control valve), incorporating a thick impervious core, excavating and keying the foundation into underlying strata, providing downstream and upstream erosion protection, and a toe drain to limit downstream seepage from compromising the stability of the dam. This would require a very expensive reconstruction of the dam and expose downstream users to increased flow risk during the construction period. A photograph of the dam is presented in Figure 11. This dam is familiar to many as a frequent location used in the television series "Breaking Bad."

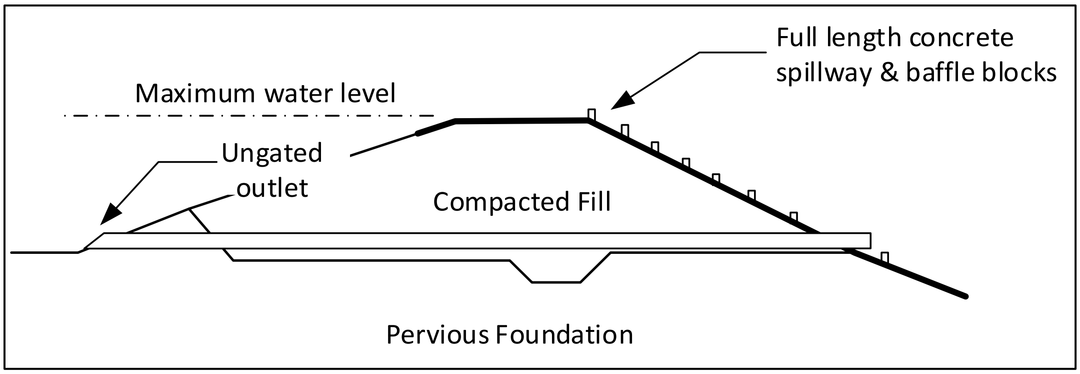

Figure 9. Schematic cross section of the John B. Robert Dam, the tallest stormwater dam in Albuquerque, New Mexico (adapted from AMAFCA files).

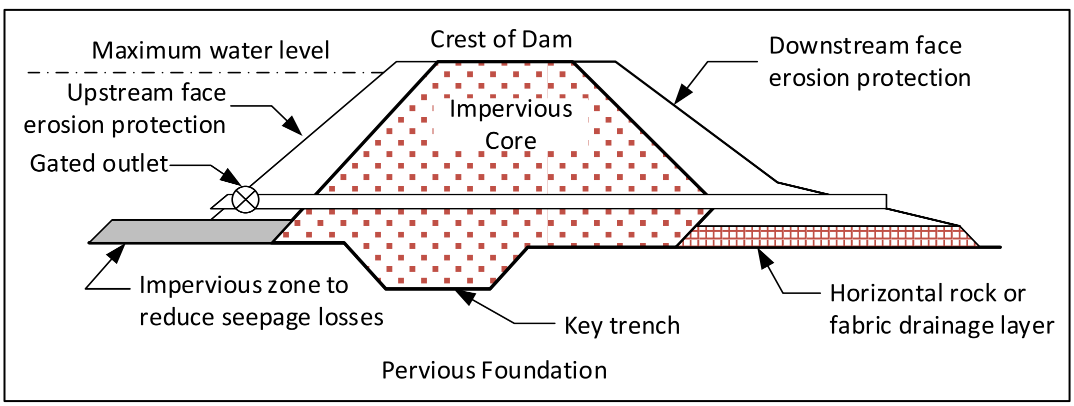

Figure 10. Illustration of principal features of an earthen dam design to retain a permanent pool of water (adapted from BOR, 1987).

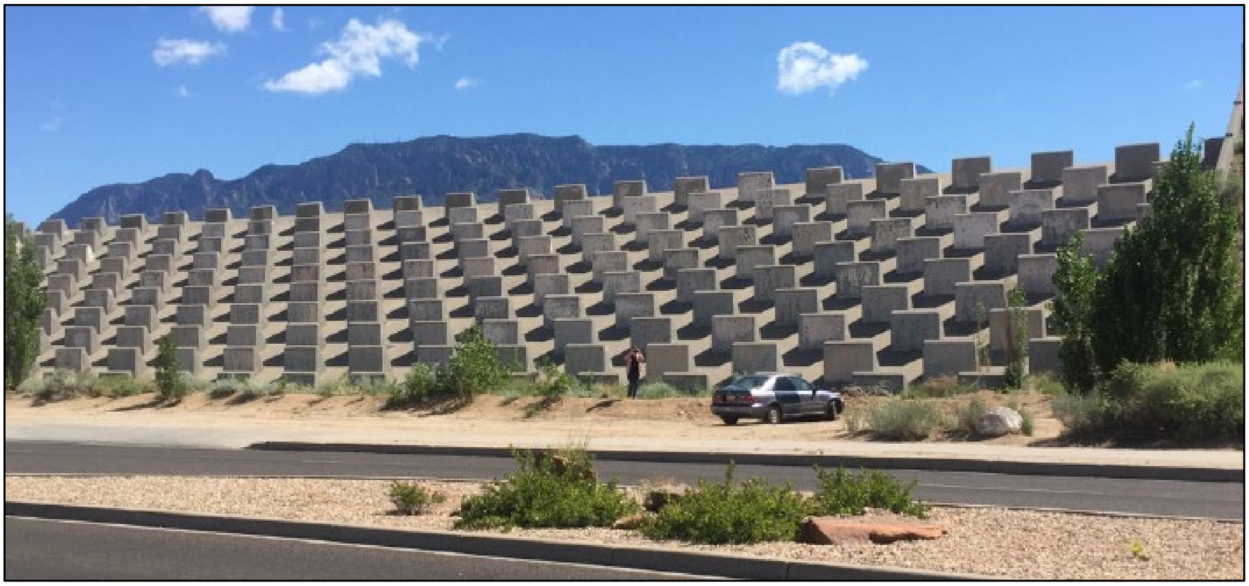

Figure 11. Photograph of the John B. Robert detention dam, a 65-ft (20 m) tall earthen dry dam owned and operated by the Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA) (photo by the author).

Convey Water to Point of Use

Urban stormwater is captured in reservoirs located in developed areas that, with few exceptions, are not near potential points of use. Reuse options in Albuquerque include diverting water from the NDC to the San Juan Chama Drinking Water Treatment Plant on the northeastern side of the river or diverting water to the canal system operated by the Middle Rio Grande Conservancy District (MRGCD), which provides irrigation to farmers in the middle Rio Grande Valley. There are no large water users or conveyance facilities near existing stormwater reservoirs in the northwestern or southeastern part of the city.

The Elephant Butte Irrigation District (EBID) operates an extensive system of stormwater dams and irrigation canals below Elephant Butte Dam on the lower Rio Grande. There are several features of these dams and canals which suggest that stormwater capture and reuse may be feasible in this area including:

- Stormwater retention in reservoirs located south of the spillway at Elephant Butte Dam do not affect deliveries to the Lower Rio Grande and Texas under the Rio Grande Compact.
- Many existing dams are located in undeveloped watersheds, which makes acquiring surrounding land needed to increase the inundation pool easier than for dams located in urban areas.
- Many of the dams are operated by EBID and located near their canals so that stored water could easily be delivered for irrigation consistent with their irrigation needs.

An example of a potential stormwater capture and reuse project at one of the EBID dams is presented below.

An alternative to capture, storage, treatment, and use of stormwater may be to use it to recharge underlying groundwater resources (Ferguson, 1994. USEPA 2021). This would seem easy to accomplish in a location such as Albuquerque in which surface soils are dominated by high permeability silts and sands except in the ancestral flood plain of the Rio Grande. However, the flow of water through porous media is strongly dependent on the diameter of particles constituting the smallest 10% of the soil's mass fraction (Jury and Horton, 2004). Silt and clay particles in stormwater settle in ponds and reservoirs and quickly seal the bottom, which greatly reduces infiltration. Figure 12 is a photo of standing water in a farm pond after 70 days of no precipitation and illustrates limited infiltration even from an unlined pond located in sandy soil. A sidebar discussion of local experience with infiltration from an unlined stormwater reservoir is presented below.

Figure 12. Air photo of standing water in a farm pond 70 days after the last rain storm (photo by author).

Clogging of soils by sediments in urban stormwater has been recognized previously (Ferguson, 1994; Wang et al., 2012; Al-Rubaei et al., 2013; USEPA 2021). Studies to identify aquifer recharge zones in the Albuquerque basin have found that the best locations are where high energy flowing water provides continuous removal of fine particles as occurs in alluvial fans at the foot of steep mountains (i.e., mountain front recharge) (Hawley and Whitworth, 1996).

Several methods have been described to recharge aquifers using stormwater including surface infiltration basins, infiltration trenches, dry wells, injection wells, and infiltration through arroyo channel bottoms (Alam et al., 2021; USEPA 2021; Zhang et al., 2020). High concentrations of fine sediments in stormwater will result in rapid clogging of underlying soils unless the water is highly treated to remove all suspended solids. This adds considerable cost and operational complexity. However, several studies have found that stormwater rapidly infiltrates through the sandy bottom of ephemeral arroyos (Schoener, 2022; Shanafield and Cook, 2014). High energy flows during storm events re-suspend and transport fine grained sediments down the channel thereby allowing rapid infiltration of untreated stormwater. The study by Schoener (2022) is especially relevant because it was done on an unlined, sand bottom arroyo near Albuquerque. The study found that between and 64% and 81% of total runoff infiltrated during storm events.

In recognition of the large infiltration rates from undeveloped arroyo bottoms, the ABCWUA implemented a USR project in which up to 3,000 AF/yr of untreated river water is discharged to an unlined, sand bottom arroyo in northeastern Albuquerque (Miller et al., 2021a, 2021b). Although the water is not treated to potable quality, it is withdrawn from horizontal wells beneath the bed of the Rio Grande so it has low suspended solids concentrations and therefore little potential for plugging shallow soils. The effects on local and regional groundwater levels have been described by Kennedy and Bell (2023). This experience suggests that stormwater retention in a reservoir, followed by controlled release into an unlined arroyo, could be an effective method of capturing stormwater as part of a managed aquifer recharge program.

Water Quality Challenges

Urban stormwater quality is often of very poor quality and must be treated before it can be used. Its quality is highly variable, especially in arid environments and depends on several factors including the type of land development in the watershed and antecedent conditions (the length of time since the last rainfall) (NAS, 2009; EPA, 1999; Makepeace et al., 1995; Smullen et al., 1999; USEPA 2021). Chong et al. (2013) considered the chemical, toxicological, and microbial risks associated with harvesting urban stormwater as a means of supplementing municipal water supplies in Australia. They found that while chemical toxicants in stormwater were less than in recycled wastewater, the concentrations of metals including cadmium and lead were much higher due to urban road dust (Hwang et al., 2016).

The USGS monitored the quality of stormwater in NDC for nine years in Albuquerque, New Mexico, which is summarized in Table 5. Note that the median concentrations of biochemical demand (BOD), total suspended solids (TSS), and nitrogen and phosphorous compounds are all much greater than reported by the EPA (1999) for stormwater from a mixed land-use watershed. The concentrations of lead, copper, and zinc appear lower in the NDC stormwater; however, EPA reported total concentrations that include both soluble and insoluble metals. The high concentration of fecal indicator bacteria is consistent with the findings of others (Chong et al., 2013; NAS, 2009; EPA, 1999; EPA 2021). The high variability in the NDC water quality data is due in part to antecedent conditions, but more importantly, to when in the hydrograph the water samples were collected. The water quality during the rising limb of the storm hydrograph is usually quite poor as the initial runoff from a storm quickly washes contaminants from the land surface into streams and arroyos, a phenomenon referred to as the “first flush” effect. Depending on whether stormwater is used for irrigation or public supply, it almost certainly will require some treatment.

Table 5. Stormwater quality data for the North Diversion Channel, Albuquerque, New Mexico for the period 2003 to 2012 (USGS, 2015)

		Water Quality			
Parameter	**No. of Analyses**	**Min.**	**Median**	**Max**	**EPA Median***
BOD (mg/L)	17	7.2	16.1	207.0	7.8
COD (mg/L)	21	34	220	770	65
TDS (mg/L)	16	24	100	278	
pH	24	6.8	8.2	9.3	
TSS (mg/L)	23	68	1,520	6,160	67
T (C)	27	6	19	25	
NH3 & Org N (unfiltered	24	0.95	2.86	7.46	1.29
NO3 & NO2 (filtered)	23	0.26	0.61	1.24	0.56
Sol. Phosphorous (mg/L)	9	0.1	0.14	0.33	0.056
Soluble Lead (ug/L)	19	0.16	2	6.93	114.[&]
Soluble Copper (ug/L)	19	5	5.38	25.7	27.[&]
Soluble Zinc (ug/L)	11	0.01	12.4	44	154.[&]
E.coli (MPN/100 mL)	29	1	2,420	261,300	

Notes:
*Median stormwater quality for mixed land-use watersheds in the U.S. (EPA, 1999) & EPA (1999) reports total concentrations of lead, copper, and zinc

Besides water quality considerations, a project to capture stormwater for subsequent use must consider the very large volumes of sediment, trash, and debris associated with urban runoff. This material will accumulate in retention facilities, which will require frequent removal to prevent further water contamination and to preserve the volume of stormwater reservoirs. From 2016 to 2023, AMAFCA removed an average of 48,000 cubic yards of sediment and 1,700 cubic yards of trash each year from its ponds and reservoirs. The trash ranged from small items like plastic bottles and shopping bags to large items such as shopping carts and sofas. This demonstrates that collecting, transporting, and disposing of large volumes of waste material is a major operational consideration when evaluating a proposed stormwater capture and reuse project.

Sidebar Discussion – Infiltration from Ponds and Reservoirs

The vulnerability of dry dams to failure and the limited infiltration that occurs were described by Blair (2017). A small earthen detention dam owned by the City of Albuquerque failed in the early 1980s due to the presence of an inadvertent permanent pool of water behind it. At the same time, the John Robert Dam (Figure 11) had retained a small pool of water over a period of two years. Following failure of the small dam, Larry Blair, AMAFCA's Executive Engineer, ordered that the pond be drained and the saturated soil be excavated to the bottom of the wetting front. It was found that the saturated soil extended to a depth of 8 feet (2.4 m) because of plugging by fine sediments in the pond bottom. This gives an approximate infiltration rate of 4 ft/yr (1.2 m/yr) and provides additional confirmation that limited infiltration occurs through the bottom of stormwater ponds and reservoirs.

Economic Considerations

It is not possible to give guidance on the approximate costs for stormwater capture and reuse because every project will be unique and depend upon site specific and project specific variables. The principal factors that affect these costs are summarized below.

Water Rights Issues

- Costs will depend on whether the project will require acquisition of water rights for captured stormwater.

Site location

- Design storm characteristics – Intensity, duration, and frequency of storms. This, coupled with the watershed characteristics, will determine the size of the project and the volume of water that can be captured.
- Watershed characteristics – Drainage area, land cover and whether developed, soil types, topography, and arroyo/stream bed size and alignment. This information and the storm characteristics will determine the storm hydrology for the watershed.
- Proximity to point of use for captured water – This will determine the type of conveyance needed (canal, pipe, and possible pumping requirement) and its alignment.
- Availability, ownership, and cost of land – This will affect the ability and cost to obtain land for the dam, inundation pool, and right of way for conveyance structures.
- Environmental considerations – Presence of endangered species, archaeological sites, or other characteristics that will affect the ability to obtain environmental approval for the project.

Hydrology and hydraulic considerations

- Stormwater runoff characteristics – Frequency of runoff and hydrologic characteristics (peak flows and volumes) are needed to develop the size of reservoir to provide capacity for both flood protection and water storage.
- Characteristics of dam location – Dam site must be consistent with a structure for long-term storage of a pool of water, especially geotechnical stability of the dam and appurtenances.
- Cost of modifying an existing dam or constructing a new dam.
- Cost of conveyance infrastructure to transport water to point of use.

Water treatment costs depend on the ultimate use of captured water

- Irrigation use – Required treatment may be limited to removal of sediment, debris, and floating trash. The presence of other contaminants such as pesticides, herbicides, or metals may require additional treatment.
- Potable water supply – Water will require treatment to federal Safe Drinking Water Act standards. Possible blending with other surface water sources may take advantage of existing treatment capacity.
- Aquifer storage and recharge – Water will require treatment to New Mexico Groundwater Standards, which are similar to drinking water standards.

Example of a Possible Stormwater Capture Project

As discussed, stormwater discharged downstream from Elephant Butte Dam does not affect delivery requirements under the Rio Grande Compact. Furthermore, there are no endangered aquatic organisms in the Lower Rio Grande that require environmental flows in the river. Thus, projects to capture, store, and reuse runoff from these watersheds will be subject to fewer water rights constraints than runoff from watersheds upstream from the dam. Finally, the Elephant Butte Irrigation District (EBID) has a system of canals along the river that could accept captured stormwater and use it to augment irrigation supplies. An example project that has many of the attributes supporting a possible stormwater capture and reuse project is described below.

The Broad Canyon Dam is an earth filled dry dam located on the west side of the Rio Grande halfway between Hatch and Las Cruces that is owned and operated by the EBID (Fox, 1975). It was built in 1970 to provide flood protection in the Hatch Valley and Selden Canyon areas. The dam is 71.5 ft (22 m) high and 1,434 ft (44 m) long and captures runoff from a 64-square-mile (166 square km) watershed. The dam is ungated and has a storage capacity of 6,080 AF. It was designed to detain water from a 4.5 in (11.4 cm) rainfall, which will generate a flow rate of 6,630 cfs (18.8 cubic m/s). There is no irrigation canal downstream from the dam, but it is less than 3,500 ft (1,000 m) west of the Rio Grande so that stormwater is discharged directly to the river.

At first glance, this dam appears to be an attractive site for stormwater capture and reuse as the land for the dam, watershed, and inundation pool is all owned by either the state or federal government, as is most of the land between the outfall and river. However, much of the watershed is designated as a Bureau of Land Management Wilderness Area, which may complicate enlarging the dam and pool.

In principle, the Broad Canyon Dam could be enlarged to enable stormwater retention; however, it is a dry dam built on poorly consolidated alluvial sands and gravel so that a deep cutoff trench would be needed to prevent seepage under the dam. The dam is constructed of compacted fill with a central core consisting of compacted clayey and silty sand, which may not be appropriate for retaining a permanent pool of water (Fox, 1975;). Finally, a gated outlet would need to be constructed to allow control over water releases. Addressing these challenges would be expensive. Furthermore, adding control equipment to the dam would greatly increase its operation and maintenance requirements.

The cost of enlarging and reconstructing the dam would have to be offset by the value of the water recovered. Doña County in southern New Mexico is hot and dry with annual precipitation of about 10 in/yr (25 cm/yr), 60% of which occurs in the monsoon months of July through October. Average afternoon temperatures during these months are greater than 90 °F (32 °C). Furthermore, annual pan evaporation rates are greater than 100 in/yr (250 cm/yr), so that evaporation losses from a permanent pool would be large.

This example illustrates the factors that need to be evaluated for a potential stormwater capture and reuse project. Based on the limited available information, it appears that the volume of water that could be captured and stored in this watershed may not justify the costs of enlarging and operating the dam.

Conclusion

This chapter suggests that there are seven major constraints that limit the feasibility of capturing urban stormwater and using it to augment a community's water supply in arid regions.

- Urban runoff may be an important source of water to meet downstream delivery obligations and/or to provide environmental services for aquatic environments. These issues must be recognized when considering proposals to capture and reuse stormwater.
- Once it leaves private property, stormwater becomes owned by the state so that its capture and reuse requires acquisition of water rights.
- The hydrology of arid regions results in infrequent but very intense runoff events that provide little water compared to water supply needed for urban utilities.
- Capturing and storing urban runoff requires additional storage volume beyond that needed for flood control, and the dry dams would require re-construction to allow stormwater retention and controlled release of retained water (current dry dams cannot provide either function).
- Urban stormwater in arid regions is of very poor quality and would require treatment to remove large amounts of sediment, debris, and dissolved organic and inorganic pollutants.
- An alternative to direct stormwater capture and reuse might be to use the water for underground storage and recovery (USR) as part of a managed aquifer recharge project. Theory and experience suggest that the most feasible means of aquifer recharge is to facilitate infiltration through sand bottom arroyo channels.
- The cost of infrastructure to capture, convey, store, and treat urban runoff that would address the previous six constraints would be very expensive. The discussion presented in this section did not consider the economics of stormwater retention and reuse because the uniqueness of every such project would depend on the location, land use and values, and local hydrology. Therefore, generalized cost estimates cannot be developed.

These challenges were discussed in the context of the water laws, hydrology, watershed characteristics, and stormwater quality of Albuquerque, New Mexico, but they would equally apply to every municipality located in the arid southwest. The requirement to discharge stormwater to satisfy delivery requirements to downstream users and meet interstate compact obligations is especially important. Some communities in New Mexico are not subject to this constraint such as those located in closed basins or where there are no downstream delivery requirements. These communities may have opportunities for stormwater capture and reuse that would permit them to take advantage of this resource.

The regulatory constraints that limit regional stormwater capture and reuse projects are substantial. Instead, it is suggested that on-site retention and reuse (e.g., rain barrels and rooftop capture) associated with green stormwater infrastructure and low-impact development is a more realistic strategy for urban stormwater management. In addition to recovering the value of water and reducing the demand on the community water supply, this would provide a benefit of reducing the size of flood protection systems (i.e., drainage structures and detention ponds). Perhaps the most important conclusion of this discussion is that it draws attention to the multiple regulatory, hydrologic, infrastructure, and environmental factors associated with stormwater management. The analysis shows that although the stormwater capture and reuse concept has public appeal, the regulatory and infrastructure challenges are substantial so that a project to recover the comparatively small volume of stormwater water available in the arid southwest may not be feasible. As communities seek to address the conflicting challenges of water supply shortages and the need for flood protection, a holistic evaluation of all constraints is needed to develop best management practices.

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Brackish Groundwater Resources

Introduction

In the 1962 Annual Report of the Office of State Engineer, then State Engineer Steve Reynolds estimated that three-fourths of the groundwater in New Mexico is brackish or saline (Reynolds, 1962). State Engineer Reynolds is also credited with an estimate that the total volume of brackish groundwater in New Mexico is 15 BAF (19,000 km^3), a number that is frequently cited even to this day, although the information used to calculate this estimate is not known. To place this number in perspective, the total annual statewide diversions of surface and groundwater in 2020 was 3.8 M AF/yr (4.7 km^3/yr) (Valdez et al., 2024).

The distinction between fresh, brackish, and saline water is based on the concentration of total dissolved solids (TDS) in the water and is summarized in Table 6. In considering development of brackish groundwater resources, it is helpful to understand the terms used to describe the salinity of water. To put these values in perspective, the federal Safe Drinking Water Act (SDWA) secondary standards recommends a maximum total dissolved solids (TDS) concentration of 500 mg/L for drinking water though this is not an enforceable standard. The salinity of seawater is approximately 35,000 mg/L, while the salinity of produced water (PW) from O&G production in the Permian Basin (discussed in the next section) ranges from about 80,000 mg/L to greater than 200,000 mg/L (Jiang et al., 2022b).

Table 6. Terminology used to characterize brackish and saline water

Classification of Water	Total Dissolved Solids (TDS) Concentration
Fresh Water	<1,000 mg/L
Mildly Brackish	1,000 – 5,000 mg/L
Moderately Brackish	5,000 – 15,000 mg/L
Heavily Brackish	15,000 – 35,000 mg/L
Seawater & Brine	> 35,000 mg/L

The apparent large volume of brackish groundwater suggests it is an attractive source of water to meet current and future needs for decades to come. However, development and utilization of brackish groundwater resources present numerous regulatory, technical, economic, and ethical challenges that should be recognized when considering whether to include it in future water plans. Since it has seen little use in the past, brackish water is often referred to as a "new" source of water, when in reality it is almost always very old water having accumulated in deep formations over geologic time periods.

In recent years there have been several surveys conducted to support development of brackish groundwater resources in New Mexico and elsewhere. The USGS has published a nationwide assessment of brackish groundwater resources and its potential to augment existing supplies (Stanton and Dennehy, 2017; Stanton et al., 2017; USGS, 2024). A supporting study by Anning et al. (2018) described the brackish groundwater resources of the southwestern U.S. that provided a rough estimate of the magnitude of the resource in the aquifers evaluated. The only

New Mexico aquifer considered was the Rio Grande aquifer system, extending the length of the upper Rio Grande from southern Colorado to Fort Quitman, Texas. The report estimates that this aquifer contains 6.3 BAF (7,800 km^3) of water, of which 38% or 2.4 BAF (3,000 km^3) is brackish (TDS between 1,000 mg/L and 10,000 mg/L) and 3% or 200,000 AF (250 km^3) is highly saline. Anning et al. (2018) note that these are rough approximations and that more information is needed for specific locations to actually develop the resource.

The Arizona Department of Water Resources summarized the feasibility of developing brackish groundwater resources from 21 areas throughout the state (ADWR, 2017; Montgomery and Associates, 2024). Factors considered included sustainability of the resource, brine disposal challenges, land availability, cost, and regulatory and legal issues. The total estimated groundwater in storage ranged from 530 MAF (650 km^3) to 700 MAF (860 km^3). Interestingly, the study by Montgomery and Associates (2024) did not consider aquifers deeper than 1,500 ft (460 m) because they report that is the maximum depth that is economically feasible for pumping water. Most of the recent interest in brackish groundwater in New Mexico is in formations where the top of the aquifer is 2,500 ft (760 m) or deeper because, as discussed below, development of this resource does not require obtaining a water right.

A report by Kalaswad et al. (2005) for the Texas Water Development Board (TWDB) summarized brackish groundwater resources in 16 regions of the state and identified brackish groundwater resources in nearly all of them, with an estimated total volume of 2.7 BAF (3,300 km^3). More recently, the TWDB (2022) implemented the Texas Brackish Resources Aquifer Characterization System (BRACS) to characterize and quantify brackish groundwater resources in the state. The BRACS has estimated there is 3.2 BAF (4,000 km^3) of brackish groundwater (TDS of 1,000 to 9,999 mg/L) and 2.1 BAF (2,600 km^3) of saline groundwater (TDS 10,000 to 34,999 mg/L) (TWDB, 2022). The report clarifies that these are the total volumes, not the total estimated recoverable storage volumes. Total recoverable storage volume is the volume of water that can be released from storage by pumping as a result of compaction of the media and expansion of water. It is important to distinguish this from the total volume of water in the interstitial pores in the formation, which is greater.

In New Mexico, surface and groundwater resources fall under the jurisdiction of the Office of the State Engineer and until 2009, NMOSE had no authority over deep brackish groundwater, which is defined as aquifers deeper than 2,500 ft and with a TDS concentration greater than 1,000 mg/L (72-12-25 NMSA). Therefore, until 2009, entities seeking to use this water did not require a water right nor could they obtain one by diverting the resource. They simply had to file a Notice of Intent (NOI) to drill a well and extract the water. Nevertheless, development of this resource to date has been almost non-existent because of the complexity and high costs of drilling wells and desalinating the water. However, as demand for water increases and existing ground and surface water supplies are decreasing, there is increasing interest in utilizing deep brackish groundwater to meet current and future needs (D’Antonio, 2009).

Several proposals to develop brackish groundwater resources in New Mexico have been made since State Engineer Reynolds made his estimate of the magnitude of the resource. One of the most comprehensive high-level evaluations was made as a result of the Brackish Groundwater Assessment workshop sponsored by the NMOSE. The summary report from this workshop briefly described the knowledge of brackish groundwater resources, identified opportunities for further development, and described the needs for additional knowledge of the resource and how it might be developed (Land and Johnson, 2004). The report included an extensive bibliography of reports of investigations of the geology and hydrogeology of brackish groundwater resources in New Mexico that provides an historical perspective of major aquifers throughout the state. The assessment identified a target list of aquifers that appeared to be most promising for development of brackish groundwater that is summarized in Figure 13. This figure is frequently included in descriptions of opportunities for brackish groundwater development.

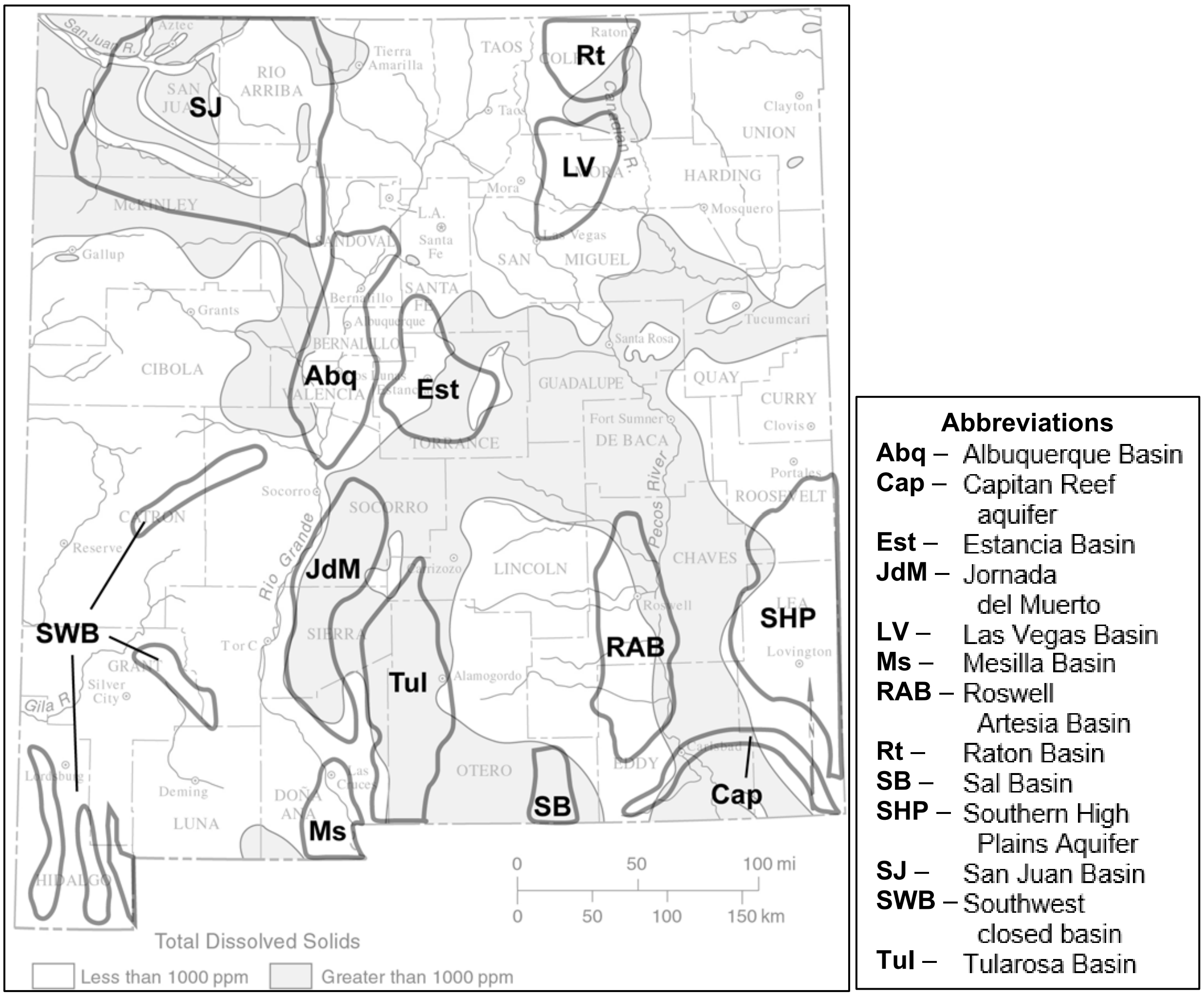

Figure 13. New Mexico sedimentary basins and aquifers with potential for production of brackish groundwater (Land and Johnson, 2004).

More recently, the state's 50-Year Water Action Plan (Grisham, 2024) proposed establishment of a State Strategic Water Supply fund to develop brackish groundwater and high salinity oil and gas (O&G) produced water (PW) for community water supply and to support the state's clean energy economy. The goal is to provide 50,000 AF of desalinated brackish water for state use by 2035 to supply water "to recharge freshwater aquifers and otherwise augment the supply of freshwater for communities, farms, aquatic ecosystems, and interstate compact compliance" (Grisham, 2024). Additional details have been provided by NMED and ERG (2024).

This chapter provides a discussion of the challenges of developing deep brackish groundwater resources for water supply. It provides a review of the regulatory status of deep brackish groundwater, a brief review of the current understanding of the hydrogeological characteristics of deep brackish aquifers, a summary of the hydraulic challenges of developing the resource, and an analysis of the challenges of desalinating brackish groundwater.

Regulatory Considerations

The New Mexico Office of the State Engineer has jurisdiction over all "declared" groundwater basins (NMSA 72-12-1) regardless of the water's salinity. A declared basin is a groundwater basin that has been formally identified by the NMOSE that is a source of water supply with "reasonably ascertainable boundaries." By declaring a basin, the State Engineer asserts jurisdiction over the basin necessary to protect owners of water rights in the basin. By 2006 all groundwater basins in the state had been declared.

Deep brackish groundwater aquifers are subject to different regulations than shallow aquifers (Bossert and Olson, 2013). In New Mexico, deep brackish water is defined as non-potable water located in confined aquifers where the top of the aquifer is greater than 2,500 feet (760 m) deep. Non-potable water is further defined as water with a total dissolved solids (TDS) concentration of 1,000 mg/L or greater. No deep brackish groundwater basins have been declared by the State Engineer; hence, a permit to develop this resource is not needed. Because use of this groundwater does not require a water right, water from these aquifers is generally considered to be a new source of supply. However, offsetting water rights will be required if pumping impacts overlying aquifers or nearby surface waters. In addition, a water right cannot be obtained from the appropriation and beneficial use of this water.

A summary of brackish groundwater policies and regulations in Texas, Arizona, Florida, and New Mexico has been provided by Buono et al. (2016) that help puts the regulatory challenges associated with this resource in perspective; however, there is little consideration of the hydrogeologic constraints. The authors offer several recommendations for streamlining the regulatory process for brackish water development while also recognizing the need to protect surface water and overlying fresh water aquifers.

Deep brackish groundwater was not subject to state groundwater regulations until 2009 when amendments were passed to place undeclared deep brackish aquifers under administration of the State Engineer (NMSA 72-12-25 through NMSA 72-12-28). Several uses are exempted from this jurisdiction including water diverted for oil and gas exploration and production, prospecting, mining, road construction, agriculture, generation of electricity, and use in an industrial process or geothermal use.

Prior to passage of the 2009 amendments, persons wishing to develop deep brackish groundwater resources did not require permission from the State Engineer, but simply had to file a Notice of Intent (NOI) to drill a well into the formation (NMSA 72-12-25; Johnson et al., 2009). The 2009 amendments took effect on March 30, 2009, so that in the months before the new regulations took effect, there was a frantic rush by developers and water speculators to file NOIs throughout the state. The NMOSE refers to these well applications as 72-12-25 wells in reference to the statute. To date, NOIs to drill 749 wells have been submitted, but only 31 new notices have been submitted since 2009 (Table 7). The locations of proposed wells in the Middle Rio Grande Basin are shown in Figure 14.

Table 7. Summary of the number of Notices of Intent (NOIs) to drill wells in deep brackish aquifers in New Mexico groundwater basins and the total intended annual volume of groundwater to be diverted (NMOSE, 2024)

Basin	No. Applicants	No. Wells	No. Wells Drilled	Proposed Diversion (AF/yr)
Upper Rio Grande	16	30		250,500
Middle Rio Grande	34	418	5	1,148,900
Lower Rio Grande	1	5		5,000
Gallup	2	59		7,000
Estancia	3	32		50,500
Hondo	2	2	2	1,000
Lea County	5	20	4	26,205
Mimbres	1	16		25,000
Upper Pecos	2	2		20,000
Curry County	1	20		25,000
Portales	1	12		25,000
San Juan	12	27	9	35,447
Tularosa	2	7		21,500
Salt Basin	5	35		143,000
Capitan	66	64	39	44,914
Totals	**153**	**749**	**59**	**1,828,966**

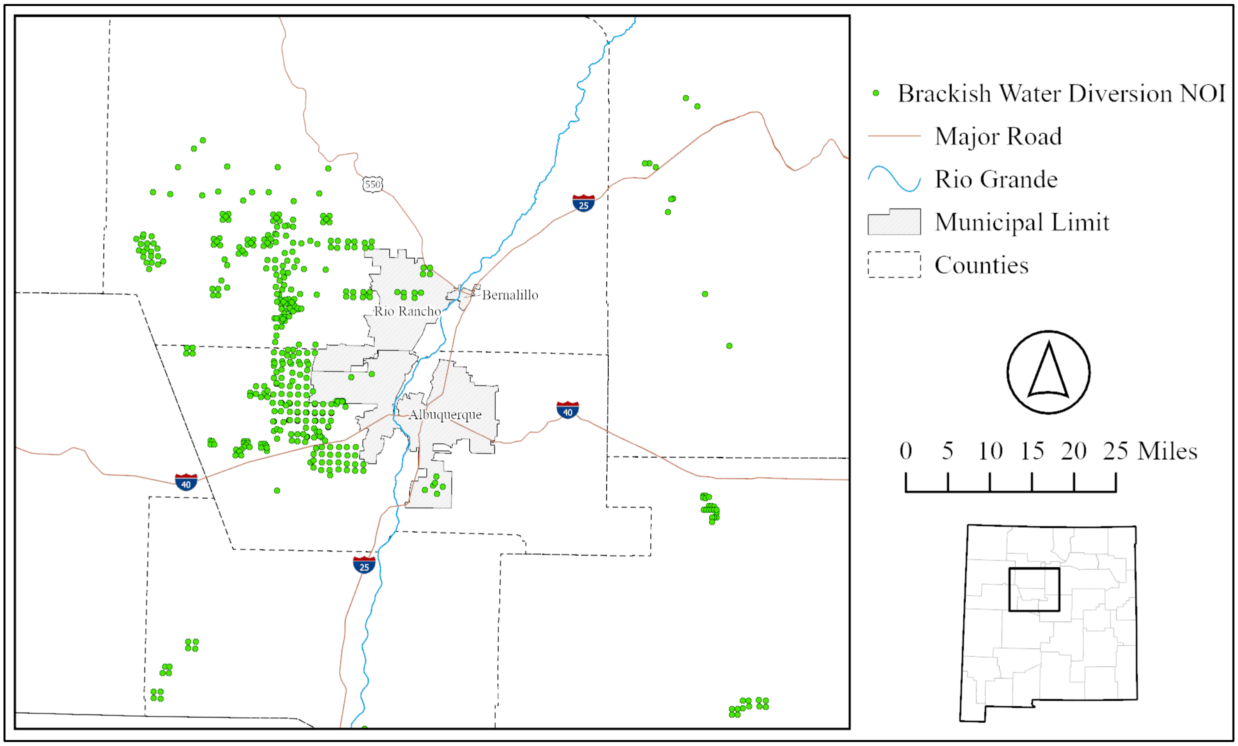

Figure 14. Locations of proposed wells in the Middle Rio Grande Basin for which notices of intent (NOIs) to divert deep brackish groundwater have been filed. (Figure prepared by Ryan Burns, NM WRRI from NMOSE data).

The NOIs that have been filed to date declare an intent to pump a total of 1.8 M AF/yr (2.2 km^3/yr) of deep brackish groundwater. Over 60% of this water would be produced by deep wells in the Middle Rio Grande Basin. Only 59 deep brackish wells have been drilled since 2009, 45 in the Capitan, Lea County, and Hondo groundwater basins of southeastern New Mexico, and nine in the San Juan Basin of northwestern New Mexico. These wells were primarily drilled to provide water for hydraulic fracturing (fracking) of O&G wells. As will be discussed in the next section, use of brackish water for fracking wells has decreased as the industry has developed methods of fracking with less expensive PW.

Although a water right is not required according to the statute (NMSA 72-12-25), the law does not explicitly state whether a water right is required to offset the effects that pumping from deep brackish aquifers might have on overlying aquifers or surface waters as a result of vertical flow through leaky aquitards or fractures in confining layers. The State Engineer has taken the position that water rights will be required to offset these impacts. A further uncertainty is whether Tribes and Pueblos have jurisdiction of deep aquifers on their lands that may be impacted by nearby pumping.

An example of the water required to offset the effects of developing a deep brackish groundwater aquifer northwest of Albuquerque was provided by Shomaker (2014). Sixty wells were proposed to produce 93,800 AF/yr (120,000 m^3/yr), although after 40 years of pumping, these wells would only produce 51,400 AF/yr (63,000 m^3/yr) of water due to regional drawdown of greater than 1,000 ft (300 m). Even though the groundwater is mostly mined (i.e., no recharge occurs), the study showed that streamflow depletion from the Rio Grande and Rio Puerco due to leakage through confining beds would eventually reach approximately 6,700 AF/yr (8,300 m^3yr). Therefore, developers of the deep brackish resource would have to acquire this volume of surface water rights to offset the impact on the rivers. A second complexity, as noted by Shomaker (2014), is that the annual volume of water available from a deep confined aquifer will decline as the groundwater head decreases due to pumping.

Recognizing that hundreds of NOIs have been filed to pump deep brackish groundwater, many of them close together (see Figure 14), introduces the question of what legal protections exist if a pumped well impairs the ability of a neighbor to develop their supply. New Mexico water law offers no relief to a landowner who suffers large groundwater drawdown under his property unless he has a pre-existing water right. But water rights are not associated with deep brackish groundwater. It is likely that the only recourse in this case would be resolution through the court system. It seems likely that the NMOSE would apply the same customary rules regarding impairment of water rights in shallow aquifers so that the result may be similar to that if the appropriation were based on a conventional fresh water permit. The regulatory uncertainty is exacerbated if the impacted aquifer underlies lands owned by Native American tribes or Pueblos.

A further regulatory uncertainty concerns whether an NOI expires. Over 90% of the NOIs filed with the NMOSE were submitted before March 30, 2009. There are no provisions in either the enabling legislation or in state groundwater regulations that establish a time limit on NOIs for deep brackish water wells. However, state water managers recognize that NOIs without expiration dates have a potential for creating future administrative problems.

Hydrogeological Considerations

In contrast to shallower fresh water resources, with few exceptions brackish water aquifers are poorly characterized due to their depth, the cost of exploration, and the fact that until recently there was little interest in developing the resource. The USGS has provided a general survey of brackish groundwater quality in Arizona, southern California, Nevada, and the Rio Grande Basin of New Mexico and Texas (Anning et al., 2018; Stanton et al., 2017). The data include depth to top of the aquifer, estimated well yields, and estimated volumes of fresh, brackish, and saline groundwater in shallow (less than 500 ft (150 m)) and deep (> 500 ft) formations. A general description of brackish groundwater resources in New Mexico has been provided by the New Mexico Bureau of Geology and Mineral Resources as part of its aquifer mapping program (NMBGMR, 2018; Land, 2016).

An early assessment of the shallow groundwater in the U.S. was done by Feth (1965). It was prepared by summarizing the TDS and depth of wells in each state. About 40 wells were used to characterize the location and depth of the shallowest brackish aquifers throughout New Mexico. Depths ranged from less than 100 ft (30 m) to greater than 1,000 ft (300 m). The report states that it was not possible to estimate the volumes of brackish water in these aquifers because "mineralized water has been looked upon generally as a liability rather than an asset," a limitation that continues today in most aquifers. Much of the information and data on New Mexico aquifers in the Feth (1965) report was provided by Hood and Kister (1962). Their report has additional detail on the major aquifers in the state and identifies the wells that were sampled to determine the groundwater quality. Moderate (>100 gal/min) yields of brackish or saline water are available in the following aquifers, listed in order of decreasing age (Hood and Kister, 1962).

- Undifferentiated rocks of Pennsylvanian age on the flanks of the southern Rocky Mountains
- The Yeso Formation of Permian age in the eastern Basin and Range Province
- The San Andres Limestone of Permian age in the Pecos Valley and near the Zuni Uplift
- The Capitan Limestone of Permian age near Carlsbad
- The Ogallala Formation of Tertiary age in the southern High Plains Province
- The Santa Fe Formation of Tertiary age in the Basin and Range Province
- Areas within the alluvium of Quaternary to Tertiary age associated with the Pecos River and the Rio Grande

A number of subsequent studies have built on the work by Feth (1965) and Hood and Kister (1962) by providing better three-dimensional delineation of brackish aquifers, more complete chemistry of the groundwater in these aquifers, and in some cases, the hydraulic characteristics of the formations. Huff (2004a and 2004b) reviewed 20 reports done between 1965 and 1983 to provide updated information on deep brackish and saline formations in the Albuquerque Basin, the San Juan Basin of northwestern New Mexico, the Roswell Basin of southeastern New Mexico, which includes the Pecos River basin, the Capitan aquifer in the Permian Basin of far southeastern New Mexico, the Estancia Basin in central New Mexico east of Albuquerque, and the Tularosa Basin of south-central New Mexico. Huff (2004a) described the general geology of each basin, provided estimates of the total volume of water in each, and gave the estimated range of hydraulic conductivities and salinity in each. The work by these and other investigators was used to develop the map of basins and aquifers with promising potential for deep brackish groundwater development (Figure 13). Hawley (2016) provided a general overview of four aquifers that are potential sources of brackish groundwater: (1) the basin-fill alluvial aquifers of the Middle Rio Grande Basin, (2) the bedrock and alluvial aquifers of the lower Pecos valley, (3) the alluvial and eolian sand deposits of the High Plains and Ogallala aquifers, and (4) the basin-fill and bedrock aquifers of the south-central New Mexico-Mexico border region.

A more complete description of brackish and saline aquifers than that presented by the New Mexico Brackish Groundwater Assessment report (Figure 13, Land and Johnson, 2004) has been developed by the New Mexico Bureau of Geology and Minerals Resources (Land, 2016; Land and Timmons, 2016) and summarized in Figure 15. The report emphasizes that maps such as this present an incomplete approximation of brackish groundwater resources because all large aquifers have hydraulic and water quality properties that vary widely depending on location and depth. Thus, groundwater might have moderate concentrations of TDS in one location and very high TDS concentrations a few miles away or in a nearby well completed at a different depth.

Description of Selected Brackish Water Basins

This section provides a summary review of brackish groundwater resources in four areas: near Albuquerque; the San Juan Basin of northwestern New Mexico; the Tularosa Basin of south-central New Mexico; and the Mesilla Basin region of southern New Mexico and northern Chihuahua, Mexico (Figure 15). All four regions have been considered for possible development as sources of future water supply. Note that this section provides a limited summary of the hydrogeology of each region along with a review of factors that may affect the suitability of each as a source of water supply. This summary is included to give an indication of the knowledge (and in many cases the lack of knowledge) of the brackish water aquifers. Descriptions of other basins have been summarized by Land (2016) and Land and Timmons (2016).

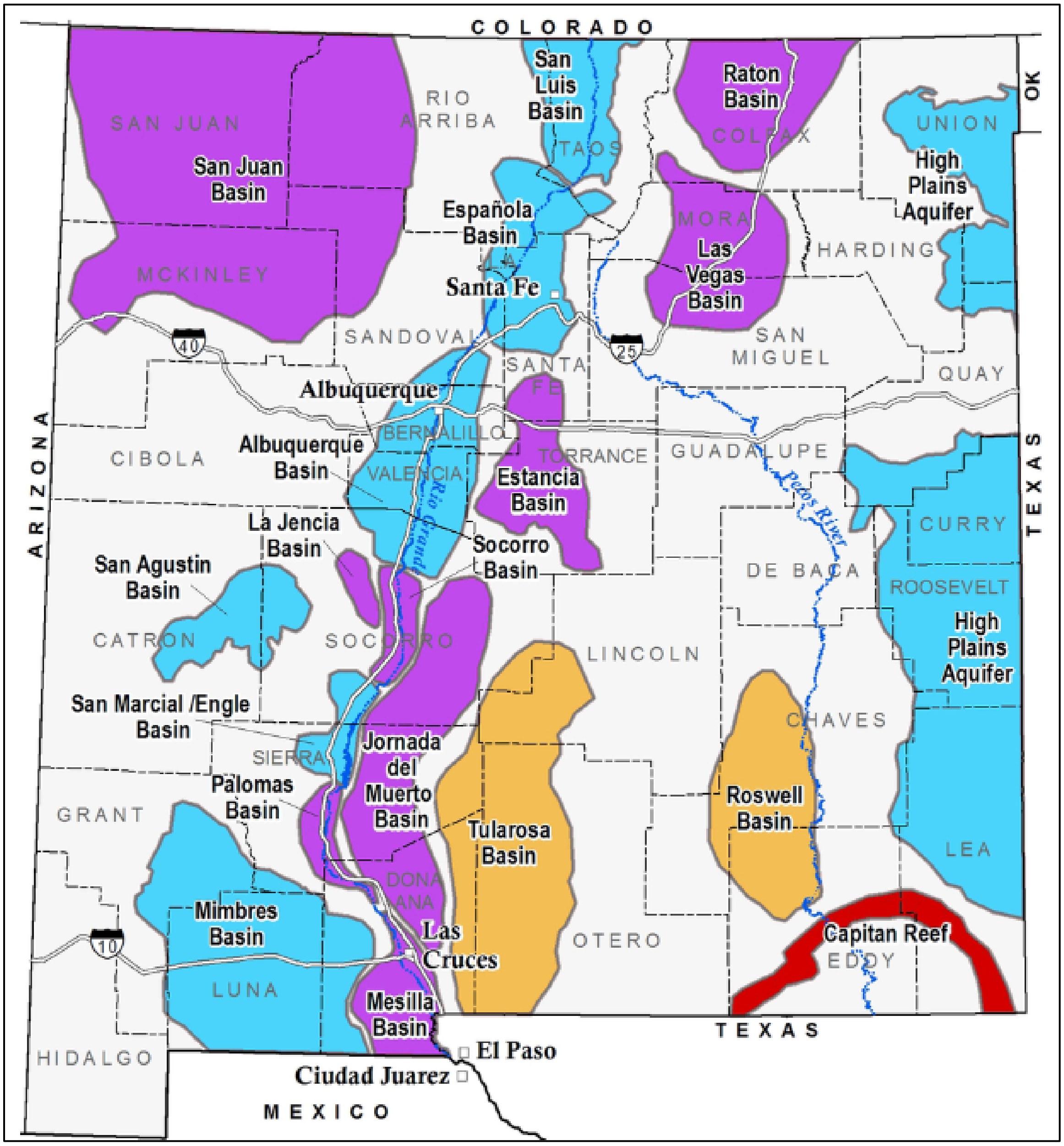

Figure 15. Brackish water basins in New Mexico (Land, 2016; Land and Timmons, 2016). The colors refer to the total dissolved solids (TDS) concentrations: Blue < 1,000 mg/L, Purple 1,000 to 3,000 mg/L, Orange, 3,000 to 10,000 mg/L and Red > 10,000 mg/L.

Albuquerque Basin

The Albuquerque Basin (see Figure 15), also known as the Middle Rio Grande Basin, is the second largest basin in the Rio Grande Rift (Land, 2016). It is bounded on the north by the Jemez

Mountains, the east by the Sandia, Manzanito, Manzano, and Lost Piños Mountains, and on the west by the Ladron Mountains, the Lucero and Nacimiento uplifts, and the Rio Puerco fault zone. Important descriptions of the hydrogeology of the basin have been provided by Hawley and Haase (1992), Kelly (2004), Thorn et al. (1993), and Connell et al. (2006). The basin is comprised of poorly cemented sands and gravels of the Tertiary-Quaternary Santa Fe Group and overlying alluvial deposits associated with the Rio Grande and its tributaries.

Groundwater resources in the Albuquerque Basin have been extensively developed because until 2008, the basin was the sole source of water supply for the City of Albuquerque and other communities in the middle Rio Grande. In 2008, the City began diverting surface water from the Rio Grande as its share of the San Juan-Chama Project water, so that surface water now constitutes about two-thirds of the utility's water supply (ABCWUA, 2019). The current understanding of the hydrogeology of the Albuquerque Basin is based in large part on the extensive geologic mapping by John Hawley and collaborators (Hawley and Haase, 1992; Connell, 2006). This work was the first to capture the subsurface complexity of the Basin and in particular, the poor hydraulic conductivity in the north and western part of the basin along with the presence of numerous faults that constrain groundwater flow.

The work by Hawley and collaborators was used to develop a three-dimensional flow model of the basin by Kernodle et al. (1996) and Kernodle (1998), which formed the basis of the model used by the New Mexico Office of the State Engineer to administer groundwater in the basin. Although this work did not address the quality of groundwater in the basin, the presence of saline water was noted at locations in these aquifers, especially along the western and northwestern boundaries of the aquifer. Other water quality challenges such as the natural presence of high concentrations of arsenic were also noted.

Shomaker (2013) described an evaluation of potential brackish water resources near Albuquerque for the ABCWUA, which considered 12 aquifers located in the Middle Rio Grande Basin, the southeastern part of the San Juan Basin, and the Estancia Basin, which is summarized in Table 8. The report identified typical thicknesses and hydraulic properties of geologic units. Shomaker (2013) summarized the range of well depths, range of expected salinity, and estimated range of well yields. The study summarized knowledge of the geologic and hydrologic properties obtained from a number of deep wells in the region ranging in depth from 2,800 ft (850 m) to 7,800 ft (2,400 m). Brief descriptions were also provided of several wells drilled to greater depths for exploration of potential O&G resources. Basic water chemistry was reported for nine deep wells that included information on the concentration of TDS, sodium, calcium, magnesium, chloride, bicarbonate, and sulfate. TDS concentrations ranged from 6,900 mg/L to 16,400 mg/L. The geology and hydrogeologic conditions are described in the report along with results obtained from drilling a number of deep wells. The focus of this report was on deep brackish water aquifers in contrast to the more general work used for the USGS groundwater flow model (Hawley and Haase, 1992; Connell et al., 2006). Note that the hydraulic conductivities for all the formations except the Santa Fe group and some of the Triassic and Permian aquifers are very small. In contrast, the range of values used in the USGS model of the Albuquerque Basin range from 4 ft/d to 70 ft/d (Kernodle et al., 1996; Kernodle 1998). The consequences of low hydraulic conductivities on groundwater development are discussed below.

Table 8. Typical thicknesses and hydraulic properties of geologic units in the southeastern San Juan Basin and Albuquerque Basin (Shomaker, 2013)

Age	Lithologic Unit	Thickness Range or Average (ft)	Hydraulic Conductivity (ft/d)	Transmissivity (ft^3/d)
Tertiary	Santa Fe Group including older Tertiary units	0 – 27,000	<0.05 – 50	
Upper Cretaceous	Mesaverde Formation to Point Lookout Sandstone	~1,500		
	Dalton Member and Gallup Sandstone			
	Lower Mancos Shale	1,200 – 2,400	0.0005 – 0.05	
Upper/Lower Cretaceous	Dakota Sandstone	1,360	0.1 – 8.3	1 – 749
Upper Jurassic	Morrison Formation			
	Todilto Limestone			
	Entrada Sandstone			
Upper Triassic	Chinle Group (shales	1,000 – 1,800	10^{-6} – 0.1	
Upper Triassic	Chinle Group (Agua Zarca Sandstone, etc.)	25 – 730	0.003 – 20	10 – 450,000
Permian	San Andres Limestone			
	Glorieta Sandstone			
	Yeso Formation	315-1,345	0.1 – 2	0.5 – 1,000
	Abo Formation	500 – 1,375	0.03 – 2	0.5 – 1,000
Pennsylvanian	Madera Limestone	1,000		
	Sandia Formation	216		
Upper Mississippian	Arroyo Penasco Formation			

The entire study area considered by Shomaker (2013) was approximately 14,800 mi^2 (38,300 km^2) and is shown in Figure 16. The hydraulic properties and expected salinity of the formations considered are summarized in Table 9, although it is important to note there are large ranges and considerable uncertainty in many of the values listed in this table. Assuming an average drainable porosity of 0.1, Shomaker (2013) estimated that the total amount of groundwater present was 3.7 BAF (460 km^3); however, he was careful to note that in deep formations water is released from storage due to expansion of water and compression of the aquifer, not by drainage from the pores. Assuming a storativity value of 2×10^{-6} per foot of aquifer thickness (an approximation first published by Lohman, 1972), and an average drawdown of one-half of the saturated aquifer thickness, the total recoverable water was estimated to be 37 MAF (46 km^3).

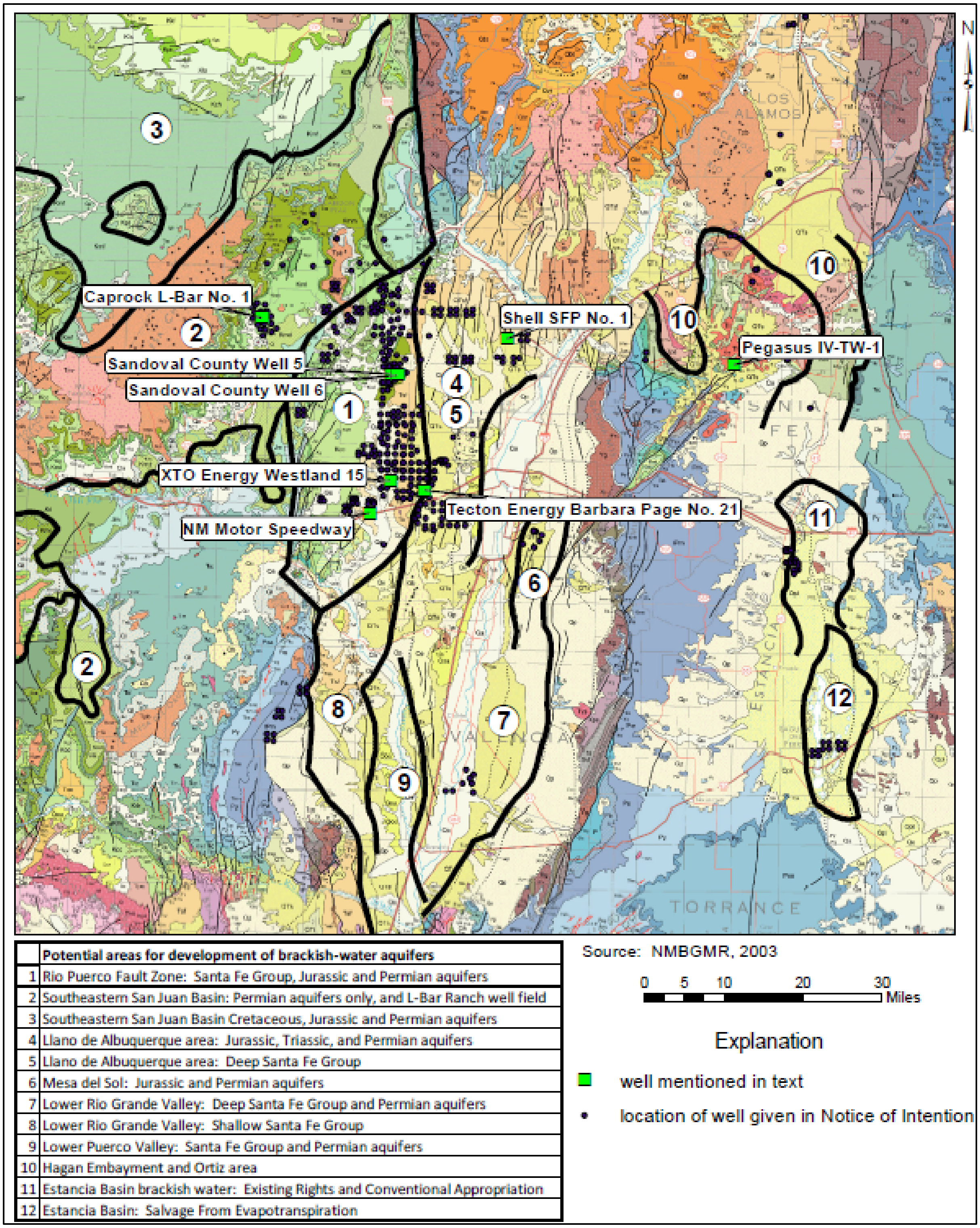

Figure 16. Geologic map showing areas for potential development of brackish groundwater near Albuquerque. Map includes location of deep exploration wells and notice of wells for which Notice of Intent to divert deep brackish water had been filed by 2008 (Shomaker, 2013).

Table 9. Summary of potential areas for development of brackish water aquifers (Shomaker, 2013)

Potential Area for Development of Brackish Water Aquifers	Range of Well Depths by Aquifer (ft)	Range of Water Quality (TDS, mg/L)	Estimated Range of Well Yields (gpm)
1. Rio Puerco Fault Zone: Santa Fe group, Jurassic and Permian aquifers	5,000 – 6,000 650 – 14,000 3,800 – 17,800	≤ 20,000 ? ≤ 20,000 ? ≤ 12,000 ?	400-600
2. Southeastern San Juan Basin: Permian aquifers only and L-Bar Ranch well field	3,700 – 6,200	≤ 20,000 ?	≤ 1,000
3. Southeastern San Juan Basin; Cretaceous, Jurassic and Permian aquifers	2,000 – 4,000 3,100 – 5,100 5,600 – 7,600	Slightly brackish? ≤ 10,000 ? ?	Small Several hundred Small
4. Llano de Albuquerque area: Jurassic and Permian aquifers	8,600 – 32,600 12,000 – 36,000	≤ 25,000 ?	≤ 1,000 ? Several hundred
5. Llano de Albuquerque: Deep Santa Fe Group	> 6,000	10,000 – 20,000	More than 500
6. Mesa del Sol: Jurassic and Permian aquifers	7,200 – 11,000 9,000 – 14,500	≤ 20,000 ?	Several hundred Several hundred
7. Lower Rio Grande Valley: Deep Santa Fe and Permian aquifers	5,600 11,600 16,000 – 25,000	10,000 – 20,000 ≤ 25,000	More than 500 Several hundred
8. Lower Rio Grande Valley: Shallo Santa Fe Group	5,000 – 8,000	3,500 – 20,000	1,000 – 2,000
9. Lower Puerco Valley: Santa Fe Group and Permian aquifers	5,000 – 8,000 ≤ 19,000	≤ 20,000 ?	More than 1,000 ≤ 1,000 ?
10. Hagan Embayment & Ortiz area: Jurassic and Permian aquifers`	> 3,000 > 3,000	?	Several hundred Several hundred
11. Estancia Basin brackish water: Existing rights and conventional appropriation	< 2,500	1,000 – 5,000	500
12. Estancia Basin: Salvage from evapotranspiration	≤ 7,000	Several thousand to 100,000 ?	Several hundred to 1,000

One of the issues identified by Shomaker (2013) was evidence of vertical flow across overlying bedding strata that provides hydraulic connection between aquifers. This may occur as a result of flow through fractures in the formation or leakage through low permeability confining zones. As discussed, the ability to withdraw water from a deep brackish aquifer without a water right is allowed only if the aquifer is not hydraulically connected to surface water or groundwater under the jurisdiction of the State Engineer. Vertical flow was identified in regional flow models of the Albuquerque Basin (Kernodle et al., 1996; Kernodle, 1998). A more recent groundwater model for a proposed project in western Sandoval County was done with an initial pumping rate of 96,000 AF/yr (120 m^3/yr), declining to 64,000 AF/yr (79,000 m^3/yr) over 40 years as head in the aquifer falls. This pumping resulted in an eventual impact of 9,000 AF/yr (11,000 m^3/yr) in flow to the Rio Grande and its tributaries (see Figure 22) (Jones et al., 2013). This impact will require acquisition of water rights to offset this depletion (Jones et al., 2013; Shomaker, 2014).

Although over 400 NOIs have been filed to develop deep brackish water resources in the Middle Rio Grande Basin (Table 7), only one project was actually implemented, a pilot project to study the feasibility of using this resource to provide water supply for a development in western Sandoval County. Details of this proposed project are described below.

San Juan Basin

The San Juan Basin is a large structural basin in northwestern New Mexico and southwestern Colorado that comprises all or parts of San Juan, McKinley, Rio Arriba and Sandoval Counties (Figure 15). The basin borders include the Nacimiento Uplift to the east, the Zuni Mountains to the south, the Defiance uplift to the north, and the San Juan Mountains of southern Colorado to the north (Land, 2016). The hydrogeology of the San Juan Basin is perhaps the best characterized of any deep groundwater basin in New Mexico as a result of more than 40 years of exploration for mineral resources, principally uranium, coal, oil, and gas. Much of this exploration involved drilling deep wells, which included careful logging of the stratigraphy encountered. Land (2016) provided a figure showing the location of more than 1,000 wells used to describe the geology and water quality, many of which reached depths greater than 4,000 ft (1,200 m).

A detailed description of the hydrogeology of the basin was provided by Stone et al. (1983), which included a widely replicated north-south cross section showing the major aquifers, confining beds, and directions of groundwater flow in the basin (Figure 17). An east-west cross section of the northern part of the basin is provided in Figure 18. Stone et al. (1983) described 15 aquifers in the region and provided several stratigraphic sections that illustrate the complex hydrogeology of the basin.

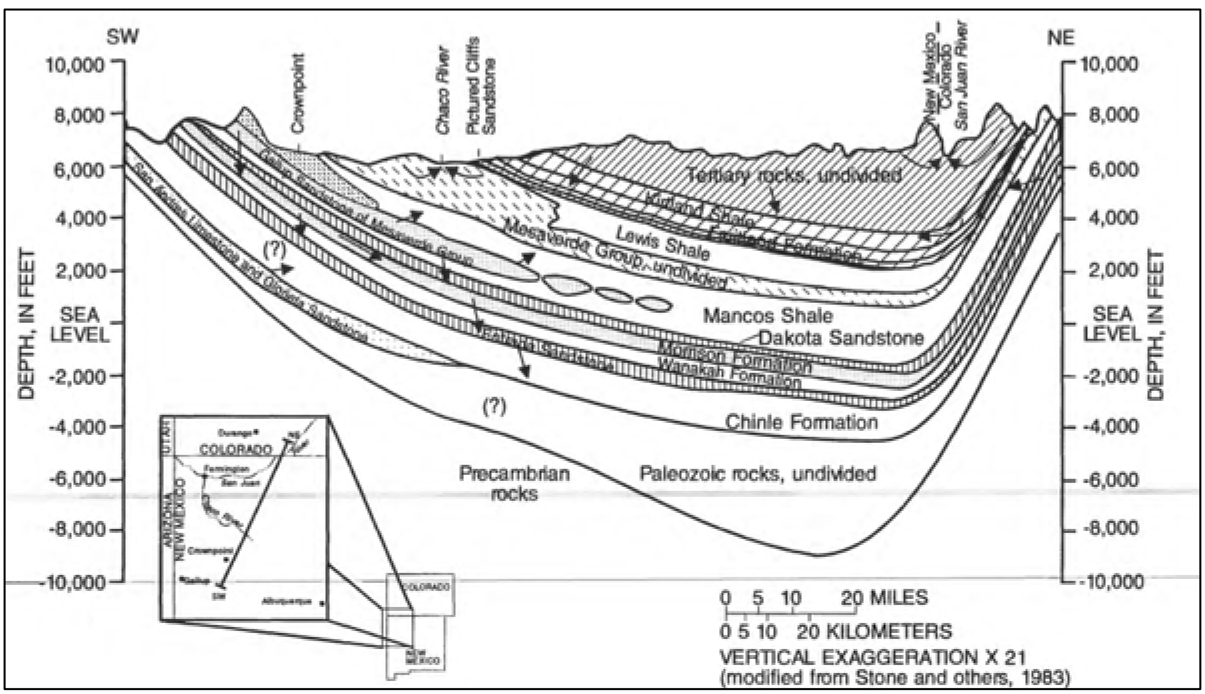

Figure 17. Generalized hydrogeologic cross section of the San Juan Basin, showing major aquifers (stippled), confining beds (bland), and directions of groundwater flow (arrows) (Stone et al., 1983).

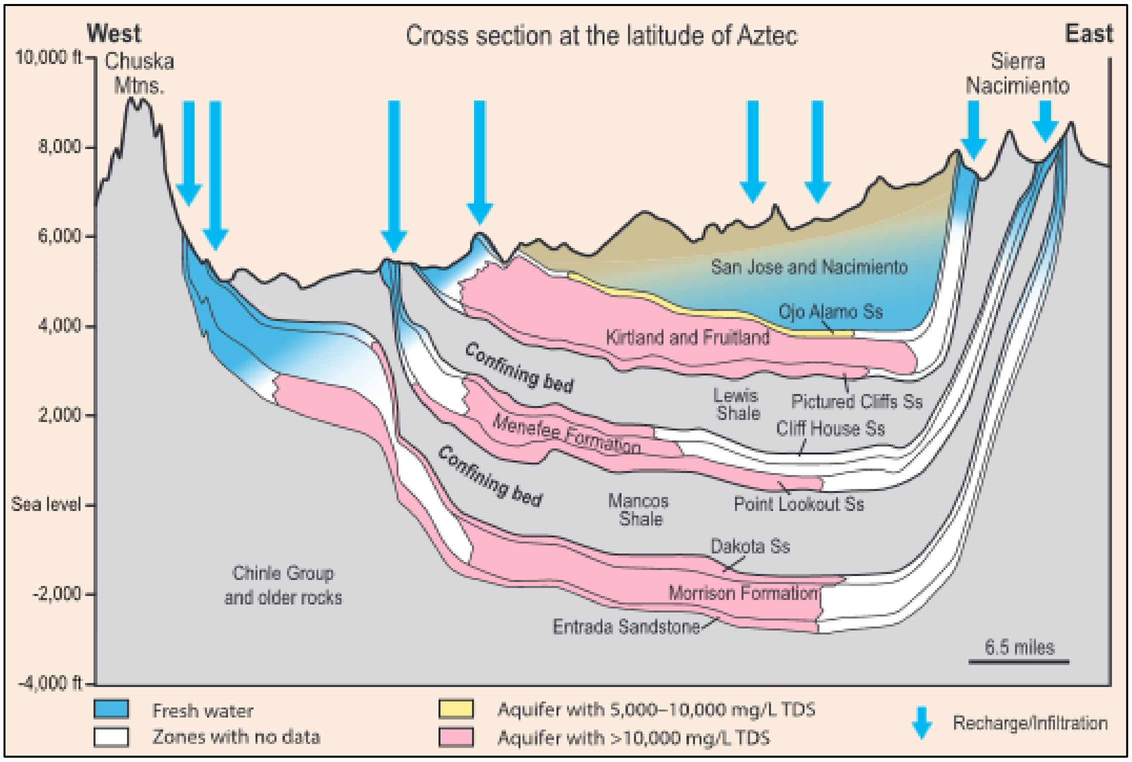

Figure 18. West to east cross section of the northern part of the San Juan Basin (approximate latitude of Aztec, New Mexico) showing major aquifers, areas of fresh and brackish water, and important recharge zones (Kelley et al., 2014).

The principal water bearing units in the basin include the sandstone aquifers of Tertiary, Cretaceous, and Jurassic age with transmissivities ranging from 25 to 500 ft^2/d. Stone et al. (1983) summarized the hydrologic properties, water quality, and groundwater use for 15 aquifers in the basin, information that was subsequently used in the development of a basin-wide groundwater model. Variations in hydrologic properties and water quality were noted but not mapped in the report so it was not possible to distinguish between locations with fresh and brackish water. A summary description of the rock units in the San Juan Basin has been provided by Kelley et al. (2014) (Table 10).

The assessment of groundwater resources of the San Juan Basin conducted by Kelley et al. (2014) was done to determine the availability of water for O&G development on the Cretaceous Mancos Shale formations. Very large volumes of water are needed for drilling and especially for hydraulic fracturing (fracking) to stimulate oil and gas production from low permeability shales and tight sands and is discussed in the next chapter. Kelley et al. (2014) provided an update of the work by Stone et al. (1983), and provided more complete information on water use, water quality, volume of water bearing formations, hydrogeologic properties, and water volumes. The report is somewhat unique in that it combines geological and hydrological data to estimate the volume of groundwater in storage in unconfined and confined aquifers at depths less than 2,500 ft (760 m) in the San Juan Basin of between 4.5 and 86 MAF (5.6 and 106 km^3). This is the volume estimated to have existed prior to development of groundwater resources; groundwater withdrawal for agricultural and domestic use, mine dewatering, O&G development, and other activities have decreased this volume. Kelley et al. (2014) noted that the actual amount of water that can be extracted from the San Juan Basin aquifers is limited by well design, especially allowable drawdown, screen length, well spacing, and other factors.

Table 10. Generalized description of the Cenozoic, Cretaceous, and Jurassic rock units in the San Juan Basin (Kelley et al., 2014)

Geologic Epoch	Formation	Rock type (Major rock listed first)	Depositional Environment	Resources
Cenozoic	San Jose Formation	Sandstone and shale	Continental rivers	Water, gas
Cretaceous	Kirtland Shale	Interbedded shale, sandstone	Coastal to alluvial plain	Water, oil, gas
	Fruitland Formation	Interbedded shale, sandstone and coal	Coastal plain	Coal, coalbed methane
	Pictured Cliffs Sandstone	Sandstone	Regressive marine, beach	Oil, gas
	Lewis Shale	Shale, thin limestones	Offshore marine	Gas
	Cliff House Sandstone	Sandstone	Transgressive marine, beach	Oil, gas
	Menefee Formation	Interbedded shale, sandstone and coal	Coastal plain	Coal, coalbed methane, gas
	Point Lookout Sandstone	Sandstone	Regressive marine, beach	Oil, gas, water
	Crevasse Canyon Formation	Interbedded shale, sandstone and coal	Coastal plain	Coal
	Gallup Sandstone	Sandstone, a few shales and coals	Regressive marine to coastal deposit	Oil, gas, water
	Mancos Shale	Shale, thin sandstones	Offshore marine	Oil, gas
	Dakota Sandstone	Sandstone, shale and coals	Transgressive coastal plain to marine shoreline	Oil, gas, water
Jurassic	Morrison Formation	Mudstones, sandstone	Continental rivers	Uranium, oil, gas, water
	Wanakah/ Summerville/Crow Springs/Bluff	Siltstone, sandstone	Alluvial plain and eolian	
	Entrada Sandstone	Sandstone	Eolian sand dunes	Oil, gas, water

Kelley et al. (2014) note that salinity does not systematically increase with depth for most of the San Juan Basin aquifers; however, fresh water is generally found at depths of <2,500 ft (760 m). Salinity is generally highest near the center of the basin. Two notable exceptions are the Gallup Sandstone with fresh water at depths to 3,500 ft (1,000 m) and the Morrison Formation with fresh water at depths to 5,500 ft (1,700 m). The latter fact is notable because the Westwater Canyon Member of the Morrison Formation has been a major source of uranium mining so that much of the water that was pumped to the surface and disposed of from past mine dewatering consisted of high quality fresh water (Thomson and Heggen, 1983).

A quantitative model of the groundwater resources of the San Juan Basin was developed by Kernodle (1996) for the USGS as part of a larger study to determine the availability and quality of groundwater in the basin. This model simulated groundwater flow in 12 hydrostratigraphic units representing all of the major water bearing formations in the basin and the confining strata that separate them. In order to develop this model, Kernodle performed a thorough review of studies of the hydrogeology of each of the aquifers in the basin as well as their depth, and areal and vertical dimensions; this summary has been used in subsequent studies. Kernodle (1996) also developed estimates of the runoff, evapotranspiration, sublimation, and recharge. Estimated annual recharge rates range from less than 0.01 in/yr (.25 mm/yr) to greater than 0.15 in/yr (.38 mm/yr). The principal recharge zones are near the basin boundaries. Critical to consideration of the basin's potential as a source of water was the finding that nearly all of the precipitation is lost to the atmosphere through evapotranspiration or sublimation and therefore "is not an element in the ground water system." Basin-wide recharge was estimated to be 0.14 in/yr (.36 cm/yr) or about 1% of the average annual precipitation in the basin. The Kernodle model was a steady-state model because the absence of historical discharge data and piezometric heads in most of the formations did not provide sufficient information over time needed to calibrate a transient model.

A subsequent model of the same region on northwestern New Mexico was developed as part of the Draft Environmental Impact Statement for the Roca Honda Mine on the northwestern flank of Mount Taylor (U.S. Forest Service, 2013). This model was developed to model the groundwater impacts of a proposed underground uranium mine. It was based on the same framework and hydrogeologic characteristics developed by Kernodle (1996), but incorporated more recent data, including flow data, which allowed simulation of transient conditions through 2125 (13 years of mine operation followed by 100 years of groundwater recovery). Mine dewatering would require pumping 7,300 AF/yr (9,000,000 m^3/yr) from the Morrison Formation at depths ranging from 1,650 ft to 2,600 ft (500 m to 790 m). The model predicted over 1,800 ft of drawdown near the mine after 13 years of mining with a cone of depression nearly 20 miles in diameter. This illustrates the very large drawdown caused by pumping large volumes of water from a deep aquifer. Note that the volume pumped is roughly one-fifth that proposed for a development in western Sandoval County discussed later in this section.

A comprehensive model of the surface and groundwater hydrology of the southeastern half of the San Juan Basin was developed by Ritchie et al. (2023) to analyze the response of water resources in the Rio San Jose Basin in response to historical water use. The model, known as the Rio San Jose Integrated Hydrologic Model (RSJIHM) includes algorithms to simulate precipitation and evapotranspiration, surface water hydrology including stream flow routing, surface and groundwater diversions for irrigation and potable water supply, and groundwater hydrology including infiltration. The surface water and groundwater models were decoupled due to long run times and numerical instabilities. Instead, the surface model was run first and the results were used to provide input to the groundwater model.

The groundwater model consisted of 500 m by 500 m grid spacing and eight horizontal layers ranging from late quaternary to Precambrian formations, for a total of 405,000 cells. The groundwater model captured a level of complexity not considered in previous models, including barriers to groundwater flow such as faults, volcanic vents, and igneous dikes. The groundwater model was so large and complex that it required a supercomputer to run. The calibration process provided information on hydraulic conductivity, vertical anisotropy, specific yield, and specific storage values for each hydrogeologic unit.

According to the RSJIHM model, the annual steady-state water budget for the Rio San José Basin included the following (Ritchie et al., 2023):

- 1,300 AF/yr (1,600,000 m^3/yr) of groundwater pumping
- 1,600 AF/yr 2,000,000 m^3/yr) of interbasin groundwater flow to the Middle Rio Grande Basin
- 25,000 AF/yr (31,000,000 m^3/yr) of groundwater discharge to streams and springs
- 1.1 AF/yr (1,400 m^3/yr) of seepage to Bluewater Lake
- 28,000 AF/yr (35,000,000 m^3/yr) of surface water recharge to the groundwater system

The transient simulation of the groundwater budget for the basin is shown in Figure 19, which shows a cumulative decrease in aquifer storage of about 590,000 AF (730,000,000 m^3/yr) over the period of 1950 to 2020. Much of this occurred between 1950 and the 1970s as a result of mine dewatering and subsequent municipal development, which increased from 13,000 AF/yr (16,000,000 m^3/yr) to 30,000 AF/yr (37,000,000 m^3/yr). While this depletion represents that which occurred from eight modeled aquifers in the entire eastern half of the San Juan Basin, it is an indication of the limits of future deep groundwater resources because it shows that the basin is not being replenished by recharge and shows that future groundwater development will result in further depletions. In other words, future groundwater development will not be sustainable.

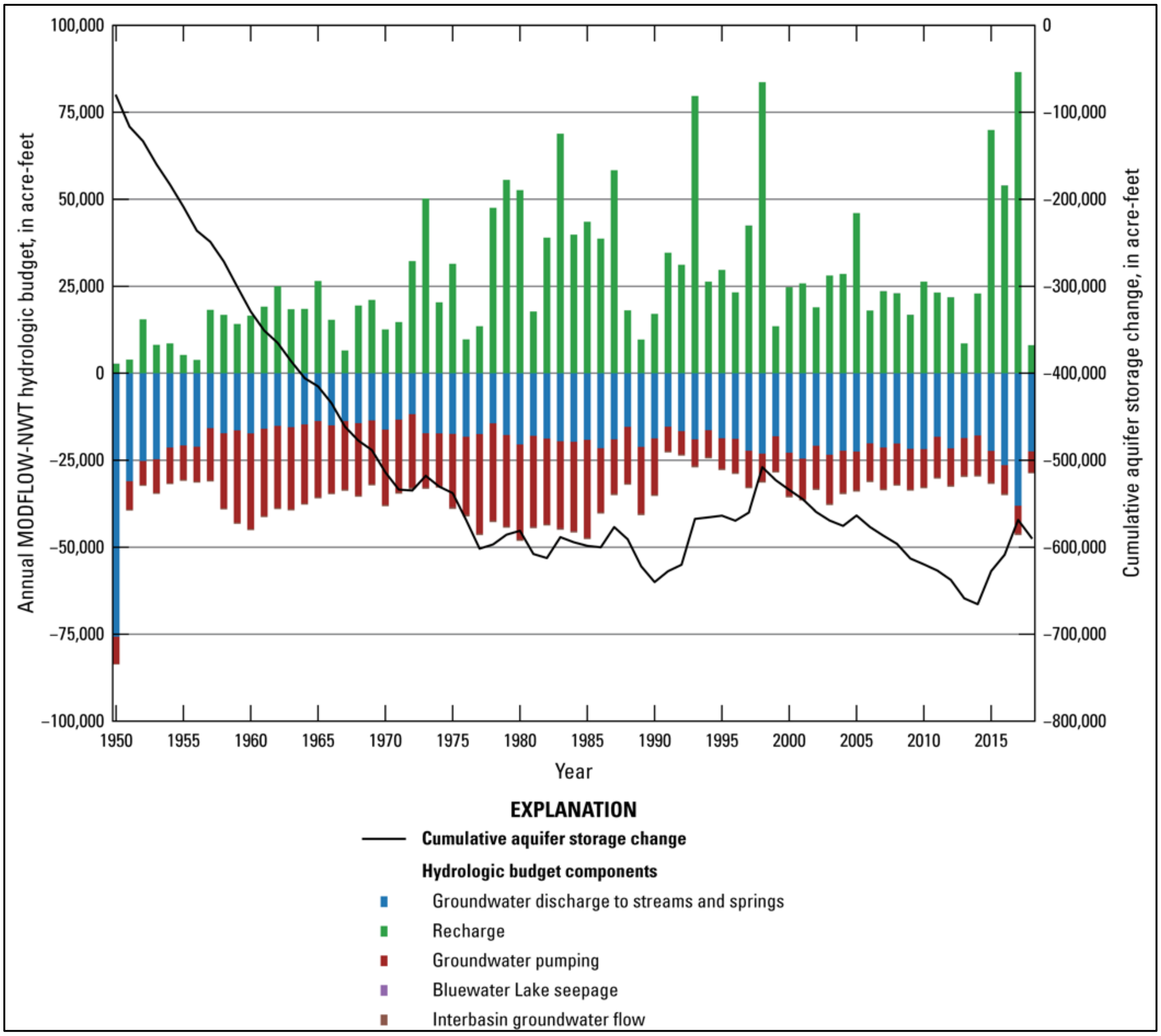

Figure 19. Modeled hydrologic budget for the Rio San José Basin and cumulate change in aquifer storage for the Rio San José Basin (Ritchie et al., 2023).

While the RSJIHM captures much of the complexity of the hydrogeology of the eastern portion of the San Juan Basin, its relatively coarse grid size of 500 m x 500 m limits its utility for evaluating the local effects of a specific groundwater development project. Other limitations of the model are that it is not well calibrated in part due to its complexity, and it is so large and complex that it must be run on a supercomputer which makes evaluation of future development of water resources in the basin difficult.

A groundwater flow model that focused on deep bedrock aquifers of the Middle Rio Grande and eastern portion of the San Juan Basin was developed by Jones et al. (2013) for the New Mexico Interstate Stream Commission. The investigators were able to use unpublished information on hydrogeologic properties developed over the course of many years by John Shomaker and Associates, Inc. The model was developed principally to evaluate the potential for development of water supplies from deep, saline aquifers in bedrock units beneath the western margin of the Middle Rio Grande Basin, and especially aquifers west of Albuquerque and Rio Rancho that have been identified in hundreds of Notices of Intent (NOIs) as future sources of water supply (Table 7). The extent of the Jones et al. model overlaps with the RSJIHM model by Ritchie et al. (2023) and is shown in Figure 20. The Jones et al. (2013) model is less complex than the RSJIHM model in that it was specifically developed to understand the consequences of deep groundwater pumping and it was not coupled to a model of surface water hydrology. Instead, it used recharge information from previous studies as input to the model.

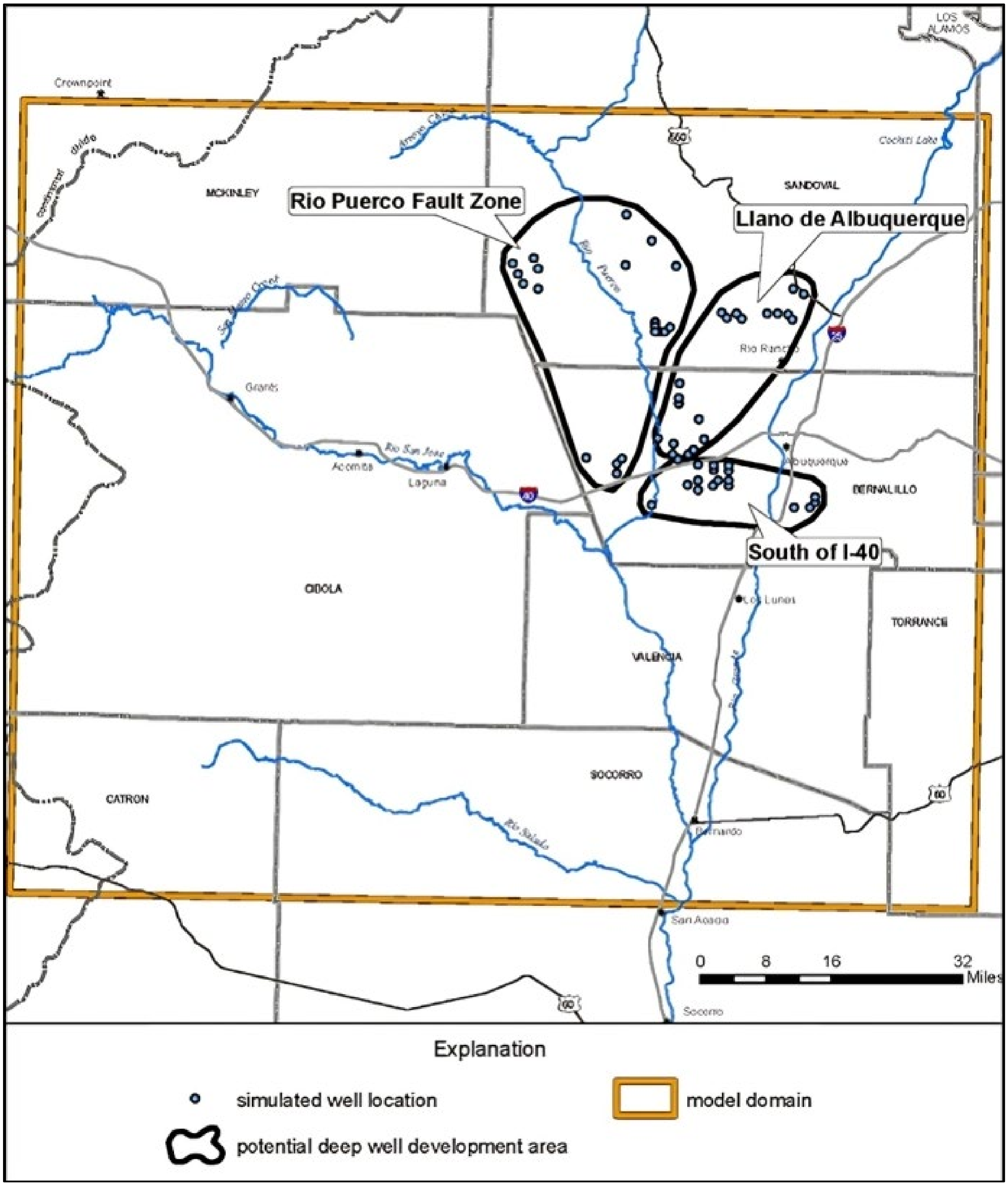

Figure 20. Boundaries of the groundwater model developed by Jones et al. (2013) showing the location of simulated deep-aquifer pumping wells.

The Jones et al. (2013) model was built upon a framework of the MRG model by Kernodle (1996) and its subsequent refinement by McAda and Barroll (2022). The model is divided into nine layers with uniform horizontal grid spacing of 1 km by 1 km for a total of 265,000 cells.

The model was developed to evaluate the effects of groundwater pumping in three target areas near the eastern boundary of the San Juan Basin as shown in Figure 20. Three scenarios were considered: low-, intermediate-, and high-level groundwater development over 40 years. Low-level development consisted of an average withdrawal of 8,400 AF/yr (10,000,000 m^3/yr) from two wells in each area. Intermediate-level development averaged about 43,000 AF/yr (53,000,000 m^3/yr) from 10 wells in each area. High-level development consisted of 20 wells in each area pumping an average total of 80,000 AF/yr (100,000,000 m^3/yr).

The principal objective of the model was to determine drawdown and impact on surface water resources for each scenario. The projected drawdown for the intermediate development scenario is shown in Figure 21. The initial pumping rate was 48,000 AF/yr (59,000 m^3/yr), which declined to 37,300 AF/yr (46,000,000 m^3/yr) after 40 years due to declining groundwater heads in the deep confined formations. Drawdown in the three pumping centers is projected to range from 807 to 3,000 ft (243 to 910 m). These large drawdowns will increase the pumping costs for any deep well development project.

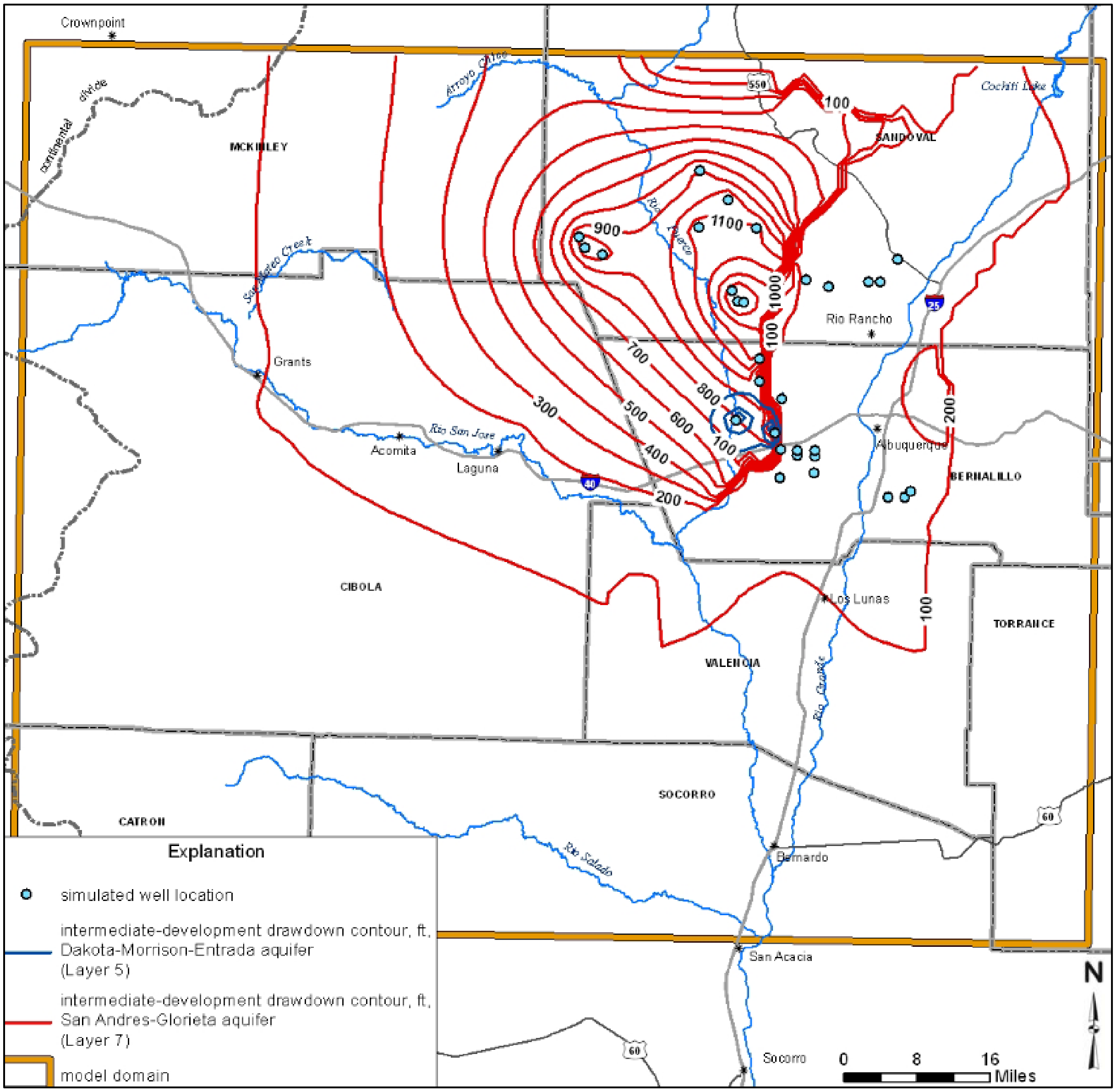

Figure 21. Projected piezometric head declines after 40 years of groundwater withdrawal for the intermediate-level development scenario (Jones et al., 2013).

The deep brackish aquifers that were the subject of the analysis by Jones et al. (2013) are considered to be confined and have not been "declared" by the NMOSE; therefore, in principle they can be developed without requiring water rights. However, leakage from overlying formations will increase as groundwater heads fall. In addition, recharge of overlying aquifers and near the boundaries where they extend to the surface will have an impact on surface streams and rivers. This cumulative impact is shown in Figure 22, which shows a reduced discharge of 3,000 AF/yr (3,700,000 m^3/yr) and 2,500 AF/yr (3,100,000 m^3/yr) to the Rio Grande and Rio San Jose/Rio Puerco systems, respectively, after 40 years of development. Surface water depletions resulting from the high-level development scenario would reach about 4,500 AF/yr (5,600,000 m^3/yr) for both river systems. Therefore, pumping from the deep brackish water formations for water supply would require obtaining water rights to offset these depletions.

The impact of deep pumping on surface water resources and the requirement to obtain offsets has been discussed by Shomaker (2014).

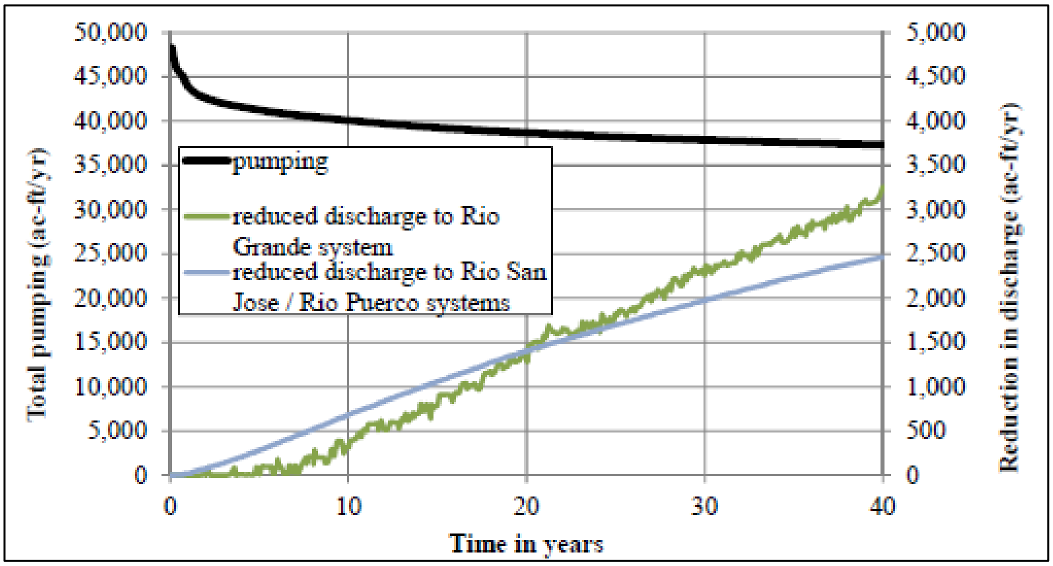

Figure 22. Projected decreases in surface water resources as for the intermediate groundwater development scenario (Jones et al., 2013).

Mesilla Basin Region

The groundwater resources along the New Mexico-Texas-Mexico border, sometimes referred to as the Transboundary Rio Grande region, have been the subject of recent investigations to determine their potential to meet the rapidly growing demand for water for municipal and industrial consumers near Las Cruces, New Mexico, El Paso, Texas, and Ciudad Juárez, Mexico (see Figure 23). There are several aquifers in the region including the Mesilla/Conejos-Médanos Basin in Mexico, the Mesilla Basin, the Jornada del Muerto Basin, the Hueco Bolson, the Palomas Basin, and smaller nearby basins. A heroic and very detailed description of the geology and hydrogeology of the region has been provided by Hawley et al. (2025, in press). This analysis is based on decades of research by Dr. Hawley and many others; the report includes a list of 2,000 references. A more general description of the hydrogeology was provided by Robertson et al. (2021).

The shallow aquifers in the Tularosa, Hueco, Mesilla (Lower Rio Grande), and Mimbres basins have all been declared underground water basins by the NMOSE and are subject to that agency's jurisdiction. Therefore, this section is focused on deep brackish water formations, which in the New Mexico-Texas-Mexico region is primarily the Mesilla/Conejos-Médanos Basin. It is of particular interest as the aquifer on the Mexican side of the border and west of Ciudad Juárez is increasingly being developed as a major source of water for municipal and industrial water supply on the Mexican side of the border.

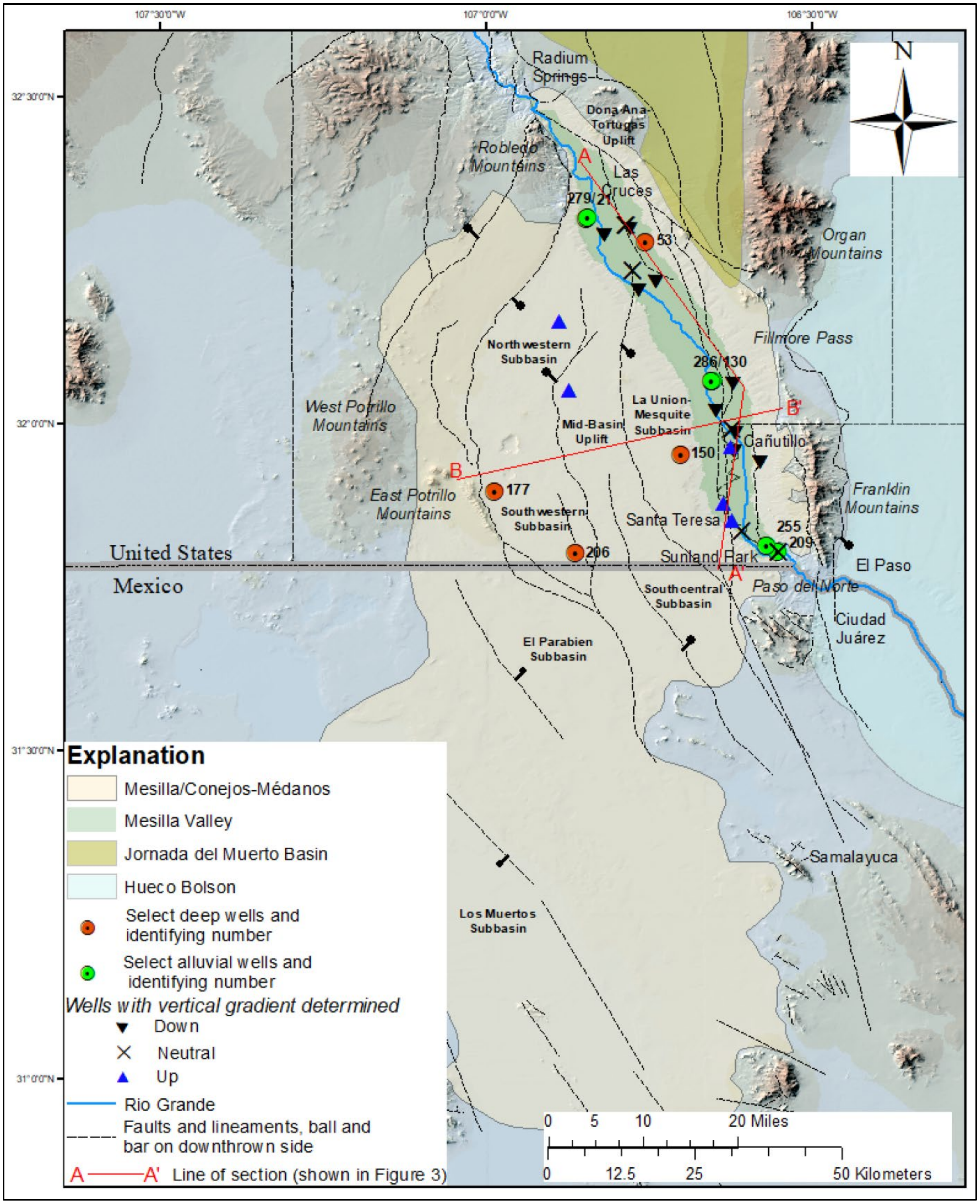

Figure 23. Map of the major aquifers along the New Mexico-Texas-Mexico border (Robertson et al., 2021).

The Mesilla/Conejos-Médanos Basin covers approximately 3,200 mi^2 (8,290 km^2), of which about 2,300 mi^2 (5,960 km^2) is located in Mexico. The Basin is semi-arid with annual average precipitation ranging from 6.6 in/yr (16.8 cm/yr) to 8.4 in/yr (21.3 cm/yr) (Robertson et al., 2021; WRRI, 2021). The stratigraphic framework consists of (from oldest to youngest) (Sweetkind, 2017):

- Pre-Cenozoic rocks including Mesozoi and Paleozoic sedimentary rocks, and Precambrian igneous and metamorphic rocks
- Paleogene sedimentary rocks and volcanic rocks
- Locally thick Neogene basin-fill deposits
- Late Pliocene to Pleistocene alluvial fan and fluvial deposits and local Pleistocene basal flows
- Late Pleistocene and Holocene deposits

Major aquifers in the basin consist of Quaternary alluvial fill deposits near the river and deeper unconsolidated deposits associated with the Santa Fe Group. The Santa Fe Group is divided into three sections, the upper, middle, and lower regions. Groundwater in the Santa Fe Group is generally present under leaky-confined conditions as a result of interbedded clays (Robertson et al., 2021). These shallower formations are under the jurisdiction of the NMOSE.

In the transboundary basin straddling the New Mexico-Texas-Mexico borders, there is a complicated interaction between surface waters of the Rio Grande and the irrigation systems, agricultural drains, and heavy groundwater pumping to supply the cities of Las Cruces, El Paso, and Ciudad Juárez. The need to understand these relationships has spurred development of several groundwater models of increasing complexity. Perhaps the most comprehensive model is the Rio Grande Transboundary Integrated Hydrologic Model (RGTIHM) developed by researchers at the U.S. Geological Survey that was first developed by Sweetkind (2017), with subsequent refinement and updates by Hanson et al. (2020) and Ritchie et al. (2023). This model was intended to be used to support development of long-term water management strategies by the U.S. Bureau of Reclamation as part of their Rio Grande Project. These reports contain comprehensive summaries of the geology, hydrogeology and surface and groundwater hydrology.

The RGTIHM is coupled to a Transboundary Rio Grande Watershed surface water model to link ground and surface water inflows and outflows. The groundwater model consists of a horizontal grid with each cell being 201 m on a side and with nine layers for a total of 806,000 active cells. The top model layer was considered to be unconfined and deeper layers were simulated as confined formations. Horizontal hydraulic conductivities of the Santa Fe Group ranged from 0.010 ft/d to 100 ft/d. Horizontal conductivities of deeper formations ranged from 0.0042 ft/d (.0013 m/d) to 10 ft/d (3.0 m/d) (Ritchie et al., 2022)

One of the complexities of combining surface and groundwater models is that the hydrologic responses to the two phenomena occur at very different time scales. Whereas change in groundwater head occurs over times ranging from years to decades, surface water flows vary over times of days to months. A recalibrated version of the model (Ritchie et al., 2022) found a decrease in groundwater storage in the last 20 years with nearly all of the depletion occurring in the shallowest formations that are most heavily pumped for municipal, industrial, and agricultural water supply (Figure 24). One objective of the model was to identify the interactions between surface and groundwater resources. The net average withdrawal of groundwater from storage shows that the basin is not in hydrologic balance, which has important consequences for federal, state, and international water management.

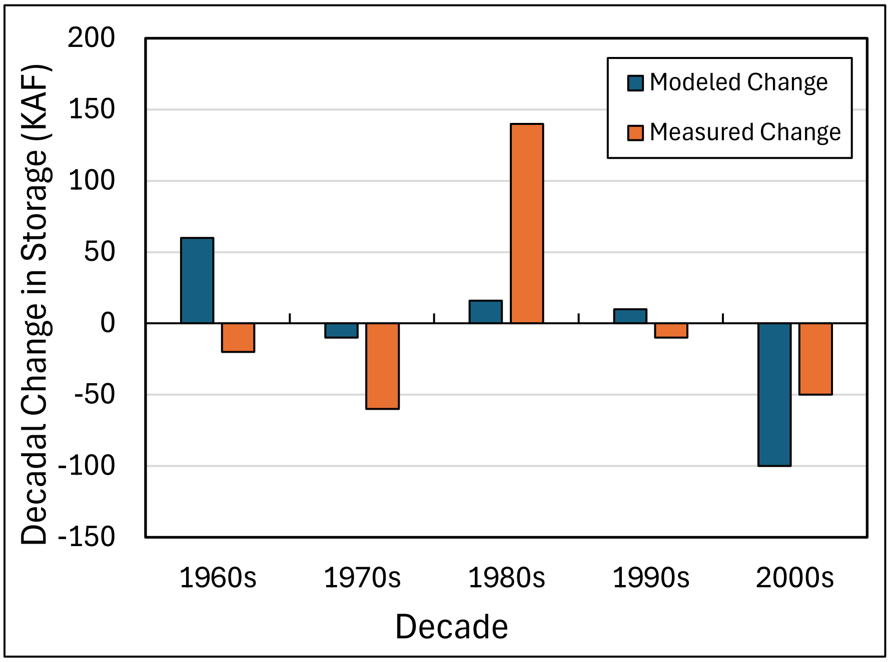

Figure 24. Comparison of the modeled and measured decadal change in groundwater storage (Ritchie et al., 2022).

The RGTIHM was focused on surface–groundwater interactions and water availability in wells in the Santa Fe Group that provide water for municipal, industrial, and agricultural uses. The model found that 89% of the total recharge in the basin went into the Quaternary alluvium and that very little recharge entered the deeper units, nor is there significant west to east flow across the numerous faults associated with rift structure of the basin. The impact of water development from deep confined aquifers on the Mexican side of the border (see Figure 25) is not discussed in USGS reports of groundwater models of the transboundary aquifers (Ritchie et al., 2022; Hanson et al., 2020; Sweetkind, 2017).

Information on the quality of groundwater in the brackish aquifers of the Mesilla/Conejos-Médanos aquifer west of the Rio Grande is limited. Land (2016) provided a general summary of groundwater quality in the basin and pointed out that most water quality data is from wells located in the upper and middle Santa Fe formation near the Rio Grande. Robertson et al. (2021) summarized the results of numerous studies on the sources of salinity in aquifers in the Lower Rio Grande and concluded that the major sources are the leaching of salts from soils by irrigation with subsequent increases in salt concentration caused by evapotranspiration and upwelling of high salinity groundwater. Frenzel et al. (1992) provided a general summary and noted the presence of geothermal anomalies and volcanic formations that contribute high salinity to deep formations. In this region, water has elevated temperatures and high concentrations of TDS, sulfate, chloride, and sodium as well as elevated concentrations of silica. The water has a specific conductance ranging from 1,400 to 2,300 microsiemens, which corresponds to approximate TDS concentrations ranging from 900 mg/L to 1,500 mg/L. A more recent report of water chemistry-based sampling and geophysical methods reported low TDS in the upper, middle, and lower Santa Fe formations near the river, but higher salinity levels along the margins of the basin, particularly to the west (Teeple, 2017).

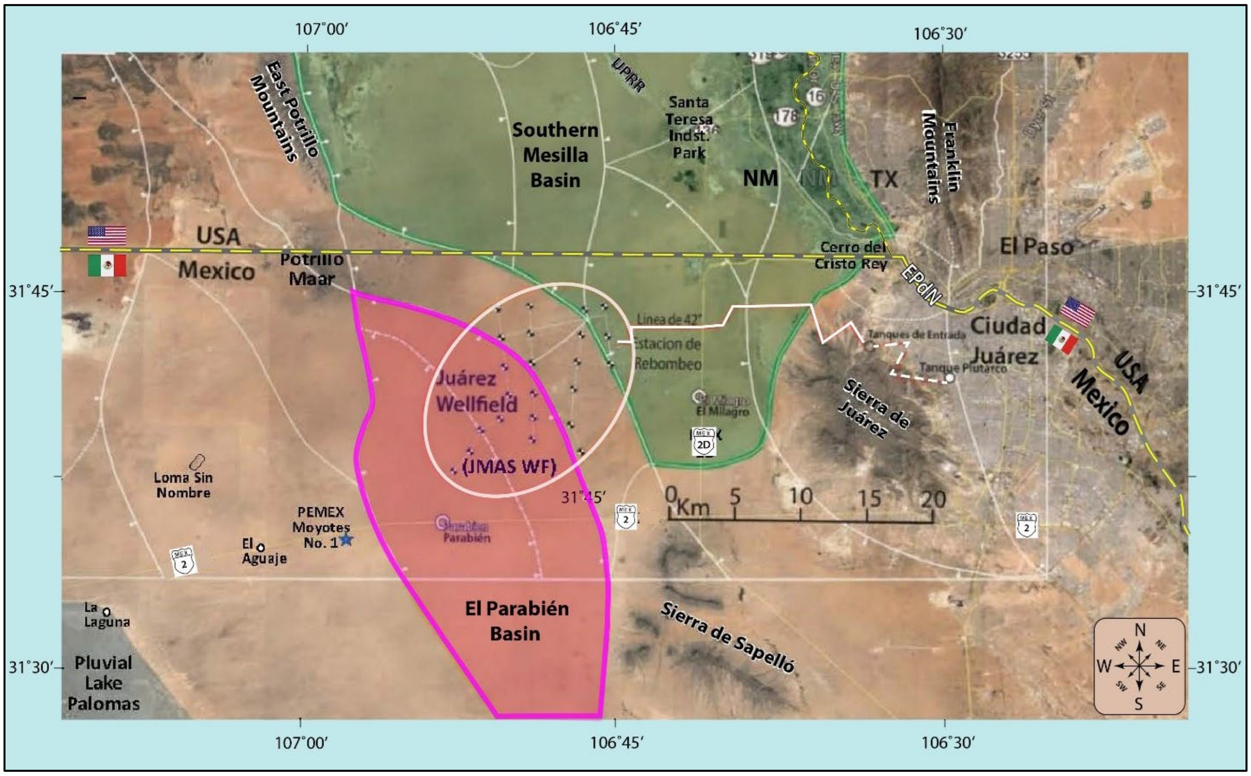

Figure 25. Map of the groundwater basins near the New Mexico-Texas-Mexico border showing the location of the Juárez well field and the water transmission line that connects it to Ciudad Juárez (Hawley et al., 2025, in press).

Tularosa Basin

The Tularosa Basin is a closed basin in south-central New Mexico extending from the Texas line north to Chupadera Mesa. It is bounded on the west and southwest by the Franklin, Organ, and San Andres Mountains, on the north by the Chupadera Mesa, and on the east by the Sacramento Mountains. The basin merges on the south with the Hueco Bolson, which underlies much of El Paso, Texas so that the basin is sometimes referred to as the Tularosa-Hueco Basin; there are no structural or groundwater divides that separate the two (Houston et al., 2021). A location map of the basin is presented in Figure 26.

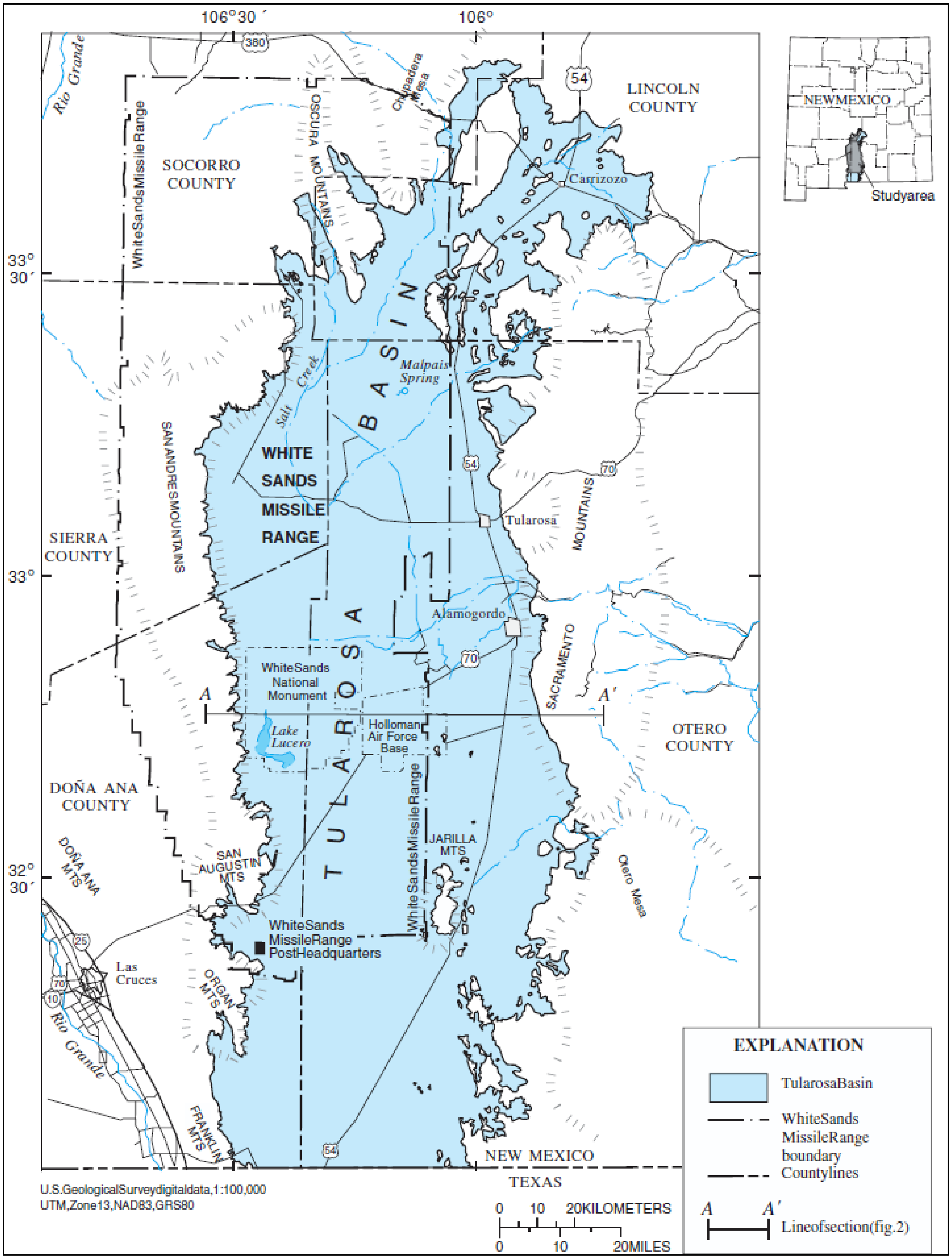

Figure 26. Location of the Tularosa basin and its boundaries (Huff, 2004c).

The definition of a hydrologically closed basin is that there are no surface water flows leaving the basin. Although there are no surface flows out of the Tularosa Basin, there is groundwater drainage to the Hueco Bolson in the south. Because there is no surface water outflow, shallow groundwater in the basin generally has high salinity (Newton and Land, 2016). The City of Alamogordo acquired rights to divert 4,000 AF/yr (5,000,000 m^3/yr) of brackish groundwater from the Snake Tank Well Field 26 miles north of town and pipes it to a 1 Mgal/d (1,100 AF/yr, 1,400,000 m^3/yr) desalination plant in town. This is the largest desalination plant in New Mexico and is designed to treat brackish water with a TDS of about 2,500 mg/L (Fowlie, 2019). Although the plant is operational, it is not regularly used because the city has been able to reduce its water demand through conservation and non-potable reuse.

The Tularosa basin is mentioned in this discussion because, although the groundwater is brackish, the top of aquifer is less than 2,500 ft deep and, therefore, is not subject to the rules under 72-12-25 NMSA. The Tularosa Basin was declared to be under the jurisdiction of the State Engineer (NMOSE, 2006), and although the groundwater is brackish, groundwater cannot be diverted without a permit from the NMOSE. The shallow aquifer is also hydrologically connected to the Hueco Bolson, which supplies brackish water to the City of El Paso.. The basin has been identified as a critical management area so diverting water from a new well would require transferring an existing water right to this well. It is interesting to note that only two notices of intent to divert deep brackish water from the Tularosa Basin have been filed under NMSA 72-12-25. These NOIs were filed in early 2009 by the New Mexico State Land Office for three proposed wells to be located on a small parcel of state land just 4.5 miles north of the border with Texas; the wells have not been constructed to date.

Desalination of Brackish Groundwater

Seawater desalination has been practiced for centuries though it has seen enormous growth in the past 50 years due to development of membrane processes, notably reverse osmosis (RO), as well as improvements in thermal processes. Eyl-Mazzega and Cassignol (2022) report that there are over 21,000 seawater desalination plants worldwide. Seawater desalination is especially important among countries on the Arabian Gulf, which represent 50% of worldwide installed capacity. For example, in this region seawater desalination provides 42% of drinking water for the United Arab Emirates, 90% of the drinking water for Kuwait, and an estimated 70% of the drinking water of Saudi Arabia (Eyl-Mazzega and Cassignol, 2022). Thus, seawater desalination processes are considered mature technologies, a conclusion supported by a 2008 report by the National Academies of Science (NRC, 2008). Nevertheless, desalination is complicated, expensive, energy-intensive, and may release large amounts of greenhouse gases depending on the source of energy used.

Desalination may be accomplished by a number of different methods that can be categorized as thermal processes, membrane processes, and other methods (Figure 27). Thermal processes are variations of distillation methods in which addition of heat causes water to transition from the liquid phase to the gaseous phase, which is then condensed to recover pure water. Membrane processes use a semi-permeable membrane in which a pressure gradient (reverse osmosis, RO), electrical gradient (electrodialysis reversal, EDR) or chemical gradient (forward osmosis, FO) is used to force water molecules through the membrane while preventing back-migration of salts or other constituents. Other methods include ion exchange (IX) and freeze desalination (FD);

however, these are niche processes and are not practical for desalinating large volumes of water. Membrane distillation (MD), and its modification, vacuum membrane distillation (VMD), is a hybrid process in which warm water, typically 50 – 90°C, is passed over a porous membrane so that water vapor diffuses through small pores in the membrane and desalinated water is condensed and recovered on the other side. Detailed descriptions of these desalination processes and variations of them can be found in recent review papers that summarize their theoretical, design, and operational aspects (Alasfour, 2020; Curto et al., 2020; Qasim et al., 2019; Salinas-Rodriguez and Schippers, 2021; Youssef et al., 2014).

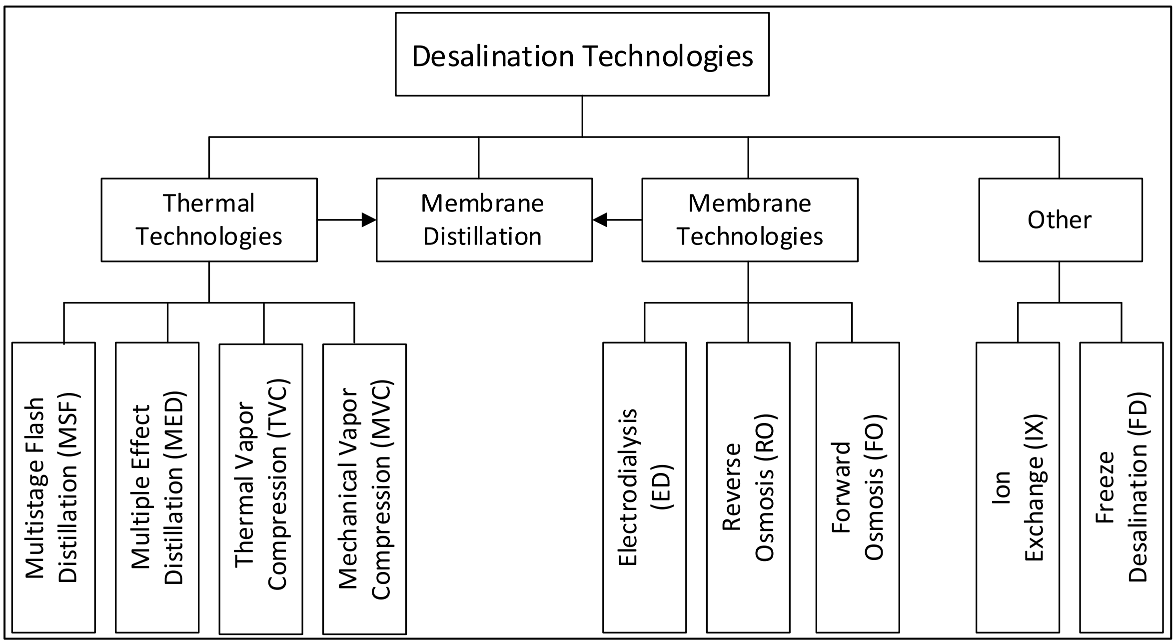

Figure 27. Summary of the most common types of desalination methods in commercial use or under development.

A flow diagram of a generic desalination plant is presented in Figure 28. The feed water is pretreated to remove suspended solids and to condition the water for optimal performance of the desalination process. This may consist of adjusting pH, removing dissolved CO_2, or softening the water to remove hardness ions (Ca and Mg). Depending on the ultimate use of the water, post treatment may consist of addition of constituents such as hardness ions or alkalinity to stabilize the water to reduce its corrosivity. Measures of the performance of a desalination process include the quality of the treated water, the fractional feed water recovery (i.e., the fraction of water fed to the plant that is recovered as desalinated water), and the energy used.

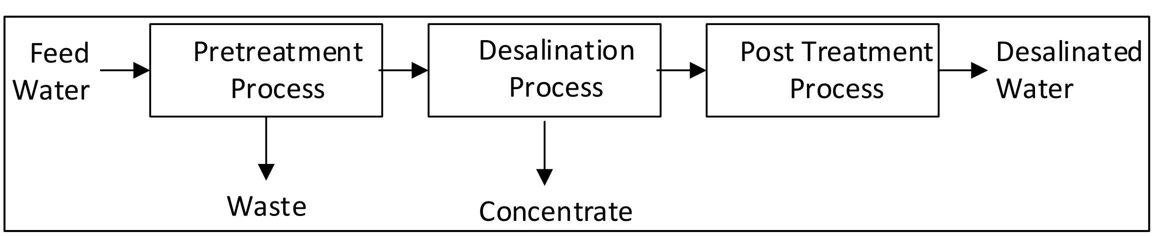

Figure 28. Diagram of a generic desalination process.

It is important to recognize that any desalination process will generate wastes that require management and disposal. The waste concentrate is particularly problematic because it contains high concentrations of salts, metals, inorganic compounds, organics, and other constituents that were removed from the feed water. When desalinating groundwater, the concentration of toxic, hazardous, or radioactive constituents in the concentrate may be high enough that the waste requires special handling or disposal, which increases the cost and complexity of waste management.

Desalinating brackish or saline groundwater at inland locations is different and more challenging than desalinating seawater. The principal differences are: (1) the chemistry of brackish and saline groundwater is much different and more variable than that of seawater, (2) there is an unlimited supply of seawater so that operating the desalination plant at high feed water recovery is not necessary, and (3) high salinity concentrate from the desalination process can be returned to the ocean with minimal environmental impacts (Thomson et al., 2024).

Desalination Challenges Due to Groundwater Chemistry

The difference in the chemistry between seawater and brackish or saline groundwater is that high feed water recovery leads to precipitation of salts that form a mineral scale on membrane or heat transfer surfaces (commonly referred to as fouling). Feed water recovery is the fraction of water fed to the treatment system that is produced as desalinated water (i.e., it is the ratio of the volume of desalinated water produced to the volume of water fed to the system). Typical feed water recoveries of ocean desalination plants are 40% or less (NRC, 2008); high recoveries from seawater are not necessary because the ocean provides an essentially limitless water supply for desalination. In contrast, inland groundwater supplies are limited so it is desirable to recover as much of the feed water as possible while also minimizing the volume of waste concentrate.

Seawater is a relatively simple solution to desalinate because it consists of greater than 95% sodium (Na) and chloride (Cl), whereas the chemistry of groundwater is much more complex. Sodium and chloride do not form mineral precipitates except at extremely high concentrations in contrast to the minerals in brackish and saline groundwater. Therefore, a seawater desalination process has less tendency to form precipitates on membrane or heat transfer surfaces, which greatly simplifies the process.

The major ion chemistry of brackish groundwater from several important basins can be visually compared using a Trilinear diagram, also called a Piper diagram. These diagrams plot the fractions of cations (calcium, magnesium, potassium, and sodium) along with the fractions of anions (alkalinity represented as bicarbonate ions, chloride and sulfate). Figure 29 is a Trilinear diagram that compares the major ion chemistry of seawater with groundwater from five basins that have been considered for brackish water supply as well as the deep brackish groundwater well drilled for the Sandoval County pilot project. Water that is easiest to desalinate has chemistry near the right apex of each of the three diagrams, which represents waters with low concentrations of the scale-forming constituents calcium, magnesium, bicarbonate, and sulfate. Groundwater chemistry within each basin varies widely; the TDS ranges over at least an order of magnitude in each of the basins shown in Figure 29. The data plotted in this figure are based on the median concentrations of each constituent reported by Land (2016), nevertheless the plots illustrate the contrast between groundwater and sea water.

Because the data in this diagram are median concentrations reported by Land (2016), only the groundwater from the San Juan Basin and the Sandoval County Well are actually brackish with a TDS concentration greater than 1,000 mg/L. Regardless of the TDS, the important point represented by this plot is that in comparison to seawater (represented by the black circle), the chemistry of all of the other waters has high fractions of calcium, magnesium, sulfate, and alkalinity, which increase the difficulties of desalination.

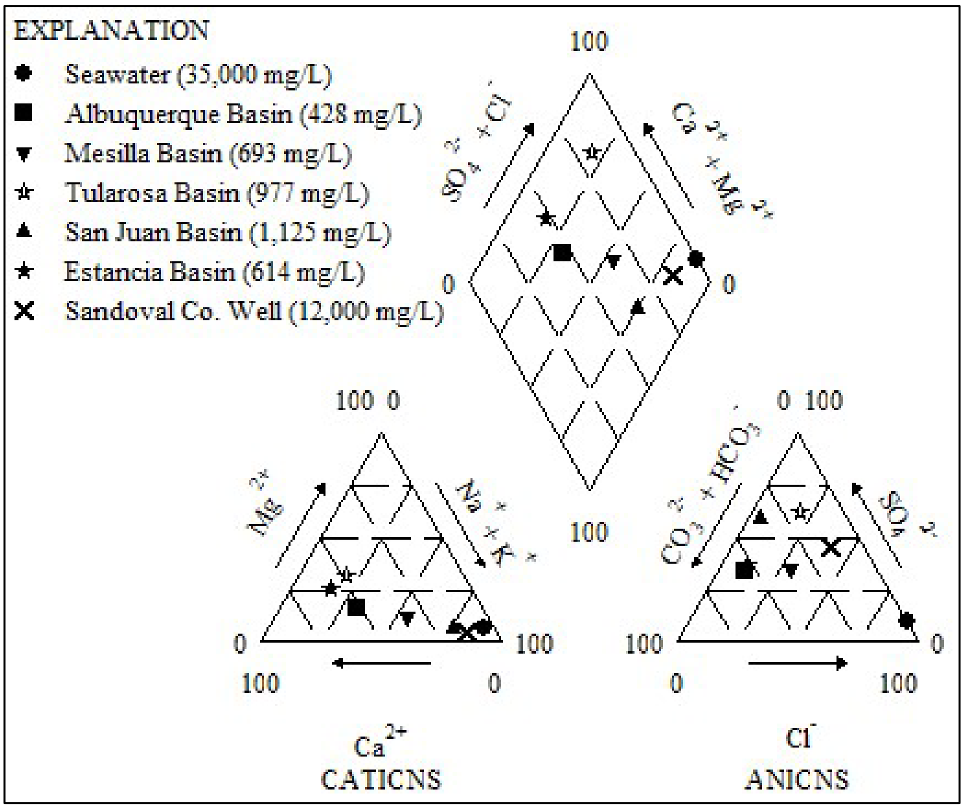

Figure 29. Trilinear (Piper) diagram summarizing the TDS concentrations and major ion chemistry of groundwater from selected basins considered for brackish water supply. The groundwater data are median values for each basin published by Land (2016). The chemistry of the Sandoval County well is from Universal Asset Management et al. (2011).

In a desalination process, as feed water recovery increases, the concentration of constituents in the waste concentrate increases, which causes precipitation of carbonate and sulfate minerals. Figure 29 graphically compares the fraction of major ions in seawater to those in representative deep brackish groundwater wells. The diagram shows that in contrast to seawater, the groundwaters all have high concentrations of scale-forming dissolved ions that complicate the desalination process. The most common mineral phases include sulfate precipitates such as gypsum ($CaSO_4 \cdot 2H_2O$) and carbonates such as calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). These precipitates can be avoided when treating seawater because the low concentrations of Ca, Mg, and SO_4 in seawater and the low feed recovery keeps the concentrations of all salts below their solubility limits. Minerals in brackish groundwater are often near their saturation limits so that membrane fouling may occur at even low feed water recoveries. Controlling scale formation can be accomplished by pretreatment such as softening to remove hardness ions, limiting feed water recovery to prevent high dissolved salt concentrations in the waste concentrate, or addition of anti-scaling compounds. Recent reviews on methods to control scale formation in desalination processes have been published by Anis et al. (2019), Ruiz-Garcia and Feo-Garcia (2017), Yu et al. (2020) and Shah et al. (2022).

Many New Mexico groundwaters also have high concentrations of dissolved silica (SiO_2), which is an especially challenging scale forming constituent. Silica is often found in groundwater at concentrations of many tens of milligrams per liter (mg/L) due to the widespread occurrence of volcanic rocks in New Mexico. As the dissolved silica concentration increases in the desalination process, insoluble precipitates form including silica ($SiO_{2(s)}$), and Ca and Mg silicates such as sepiolite ($Mg_4Si_6O_{15}(OH)_2 \cdot 6H_2O$) and diopside ($CaMgSi_2O_6$). Once formed, these minerals are almost impossible to remove from membrane or heat transfer surfaces. Preventing scale formation from silicate minerals is challenging and cleaning surfaces fouled with these minerals is very difficult.

Desalination Challenges Due to Concentrate Disposal

Desalination concentrate management is technically, economically, and ecologically challenging, especially at inland locations. For seawater desalination, the concentrate can be simply returned to the ocean, although precautions must be taken to prevent local impacts from high salinity solutions. According to Xu et al. (2013), concentrate disposal options at inland locations include: discharge to surface waters, sewer discharge, evaporation ponds, land application, and deep well injection. There is also considerable interest in zero liquid discharge (ZLD) or near ZLD in which the waste is solidified so that it can be managed as a solid waste (Xu et al., 2013). Concentrate disposal to surface waters, sewers, or land application is generally not possible due to the impacts of high salinity solutions on soils or rivers (Mickley 2001, 2012, 2013; Mackey and Seacord, 2008; Gabelich et al., 2010; Rioyo et al., 2017; Voutchkov and Kaiser, 2020). Therefore, most inland desalination plants dispose of their concentrate in deep saltwater disposal wells. An example is the KBH Desalination Plant (EPWU, 2022) in El Paso that desalinates 27.5 mgd (100,000 m^3/day) and pipes its concentrate 22 miles for deep well injection (Thomson and Howe, 2009; EPWU, 2022).

Recovery of salts and valuable minor constituents such as lithium or other byproducts may be possible but has not been successfully demonstrated at scale. Only one project is known in which commodity minerals were to be recovered from an inland desalination plant (Hightower et al., 2018; Tansel et al., 2021). A start-up company built a 2.6 mgd (10,000 m^3/day) plant to treat concentrate from the KBH Desalination Plant to recover sodium and calcium salts using a complicated process involving heat, nanofiltration (NF), degasification, electrodialysis reversal (EDR), and ion exchange (IX). Unfortunately, the company went out of business before the plant became operational. The Mineral Recovery Enhanced Desalination (MRED) project consists of a less complicated process to recover gypsum ($CaSO_4 \cdot 2H_2O$), magnesium hydroxide ($Mg(OH)_2$), and salt (NaCl) from high hardness brackish water where the principal objective was not the economic value of the commodities recovered but rather the reduced volume of waste requiring disposal (Thomson et al., 2024). It may offer a method of reducing the volume and mass of concentrate wastes requiring disposal at inland brackish water desalination plants.

A complicating factor in waste concentrate from brackish groundwater desalination is that groundwater often has elevated concentrations of hazardous or radioactive constituents. The concentration of any dissolved species in the feed water, including hazardous or radioactive constituents, increases as a function of the feed water recovery and is determined by the following relationship:

$$C_{concentrate} = C_{feed}\left(1 + \frac{rR}{(1 - r)}\right)$$

where C_{feed} and $C_{concentrate}$ are the concentration of the constituent in the feed water and waste concentrate, respectively, r is fractional feed water recovery, and R is the rejection of the dissolved constituent. For example, if a desalination system recovers 75% of the feed water (r = 0.75) and the membrane rejects 90% of dissolved ions (R = 0.9), the concentration of constituents in the waste concentrate will be approximately 3.7 times greater than that in the feed water. Therefore, if the feed water TDS concentration is 10,000 mg/L, the TDS concentration of the waste concentrate will be 37,000 mg/L.

Due to the geology of deep formations, deep brackish groundwater in New Mexico frequently has elevated concentrations of many regulated constituents, especially metals (e.g., arsenic, iron, manganese, selenium, and uranium) and radionuclides (radium and uranium). Operating the desalination process at a high feed recovery may result in such high concentrations of the metals or radionuclides that the waste concentrate becomes classified as a hazardous and/or radioactive waste. For example, the water from Sandoval County Well No. 6, a deep exploration well for a potential urban development in Sandoval County, had a feed water arsenic concentration of 0.64 mg/L and a combined radium 226 and 228 concentration of 85 pCi/L. These concentrations all exceed the state groundwater standards of 0.01 mg/L and 5 pCi/L for arsenic and radium 226 and 228, respectively. Operating a desalination plant with a recovery of 75% would increase the concentrations of these pollutants to approximately 2.5 mg/L for arsenic, which is 250 times the state groundwater standard but less than 5.0 mg/L, which is the limit for classification as a hazardous waste. Similarly, the high radium concentration in the concentrate would violate state groundwater standards. Naturally occurring radioactive materials in a water or solid material are referred to as NORM. The high concentration of radium, uranium, or other radionuclides in the concentrate from a brackish groundwater desalination process may result in the concentrate being classified as technically enhanced naturally occurring radioactive materials (TENORM). The high salinity and presence of hazardous and radioactive constituents in the concentrate waste will limit disposal options. It is likely that the only disposal option for this waste will be in a Class I injection well (EPA, 2024), although the state may approve an aquifer exemption if it finds that creating a potable water supply from desalinated water is more important than protecting degradation of a deep brackish or saline aquifer from concentrate disposal (Mercer and Fahey in Tansel et al., 2021).

Deep well injection of desalination concentrate is complicated and expensive. The subsurface formation must be protected from any phenomenon that will lead to plugging of the pore space and shorten the life of the injection well. Therefore, the water must not contain any suspended solids. Microbial growth must be prevented, usually through addition of biocides. Finally, the water must not contain any constituents at supersaturated concentrations that might cause plugging of the aquifer used for concentrate disposal as a result of mineral precipitation. Preventing precipitation may be done through use of pH control and addition of anti-scalants. For the first five years of operation, concentrate waste from the KBH plant was diluted with brackish feed water to prevent exceedance of solubility limits that would result in fouling of the formation (Mercer and Fahey in Tansel et al., 2021).

Upon initial consideration it would appear that the best option for disposal of desalination concentrate in the arid southwest would be evaporation in large, lined evaporation ponds. However, the costs of regulatory compliance, land acquisition, construction, and operation and maintenance of evaporation ponds are high. Poulson (2010) analyzed alternatives for brine management from desalination facilities near Phoenix, Arizona. The study was based on the projection that seven desalination plants would be constructed in the valley by 2035 and would require concentrate disposal. The six disposal alternatives considered include the following.

1) A pipeline to Yuma, Arizona with subsequent disposal in the Salton Sea or possibly to the Colorado River delta and then to the Gulf of California
2) Evaporation in 10 mi^2 (25 km^2) of lined ponds
3) Piping the water to the Palo Verde Nuclear Power Plant, recovering 94% of the water in a brine concentrator and disposing of the residuals in evaporation ponds
4) Softening the concentrate, recovering the water by RO and vibratory shear enhanced processing (VSEP), and disposing of the brine in an evaporation pond
5) Passing the concentrate through constructed wetlands and then discharging to the Gila River (blending would assure that the discharge did not exceed river salinity limits)
6) Concentrate disposal using deep injection wells

The projected capital and operating and maintenance costs are summarized in Table 11. The analysis found that evaporation was the second most costly disposal option and more than twice the annualized cost of deep well injection disposal. The two least expensive options, discharging the waste to a wetland and then to a river, or constructing a pipeline to the Sea of Cortez are not feasible in New Mexico, hence deep well injection is likely the only reasonable option.

Table 11. Comparison of capital costs, operating and maintenance costs, and annualized costs to dispose of 10 Mgal/d of RO concentrate near Phoenix, Arizona (Poulson, 2010) (millions of dollars)

Costs	**Yuma Pipeline**	**Evaporation Pond**	**Brine Concentrator**	**Soften/RO/ VSEP**	**Wetlands & Discharge**	**Injection Well**
Capital	$266.11	$651.69	$272.71	$286.56	$150.22	$114.46
O&M	$ 0.62	$ 3.50	$ 29.75	$ 6.90	$ 1.75	$ 11.31
Annualized Costs	$ 14.92	$ 40.26	$ 44.40	$ 22.30	$ 10.37	$ 17.46

A possible further constraint on deep well injection of desalination wastes may be induced seismicity. Injecting large volumes of fluid under high pressure into deep formations can cause earthquakes. Induced seismicity in the Southwest has been primarily associated with disposal of produced water (PW) from oil and gas development, although a small fraction of the earthquakes has been attributed to hydraulic fracturing, which is used to improve recovery of oil and gas from tight formations (Skoumal et al., 2020; Skoumal and Trugman, 2021). Factors that increase the risk of induced seismicity include the presence of faults and their proximity to the injection site, proximity of the injection zone to bedrock, injection pressures, and volumes of fluid injected (Schultz et al., 2020; Moein et al., 2023). The risk of induced seismicity will therefore be specific to a proposed project. It should be evaluated as part of project planning.

Sidebar Discussion - Case Study of a Proposed Deep Brackish Groundwater Supply Project

Currently, there are no community-scale projects in New Mexico that recover deep brackish groundwater and desalinate it to provide fresh water for public supply; thus, it is not possible to provide an analysis of the successes and challenges of the concept based on an actual case study. However, a design, drilling, and field study was begun in 2006 to evaluate development of a regional groundwater supply project to be known as the Sandoval County Wholesale Water Utility (Universal Asset Management, 2011). The project was conducted to determine the feasibility of supplying up to 43,200 AF/yr (53,000,000 m^3/yr) of fresh water to meet the future needs for municipal water supply in southwestern Sandoval County. The study consisted of a drilling program to determine the hydrogeologic characteristics of the aquifer, a pilot treatment study to determine treatability of the brackish groundwater, and preparation of a Preliminary Engineering Report (PER) to develop conceptual design criteria and an estimate of the project costs.

The location of the project is in the Rio Puerco Basin of southwestern Sandoval County approximately 14 miles west of the Rio Rancho City Center (Figure 30). Two exploratory wells were drilled in 2007 to determine the hydraulic properties of the aquifer and its groundwater chemistry. Well Exp-5 was drilled to a total depth of 6,450 ft (1,9780 m) and screened in multiple zones between 3,360 and 4,820 ft (1,000 and 1470 m), while Exp-6 was drilled to a total depth of 3,850 ft (1,170 m) and screened between 3,598 and 3,809 ft (1,100 and 450 m). Both wells were completed in the San Andres Limestone and Glorieta Sandstone aquifer (SAG). Details of the wells, the geology and hydrogeology, and the pump test are described in Appendix J of the Universal Asset Management (2011) report and by INTERA Inc. (2008). The wells are within the Rio Puerco Fault Zone identified by Shomaker (2013), which is in the southeastern portion of the San Juan Basin and separated from the Middle Rio Grande Basin by the Moquino Fault. Because of the depth of the target formation, the wells were drilled using an oil and gas mud rotary drilling rig capable of drilling to 10,000 ft (3,000 m). For this project, Well Exp-6 was evaluated as the potential source of brackish water supply. Well Exp-5 was considered for use as a disposal well for desalination concentrate, although during the testing and evaluation program, water pumped to the surface during the pilot project was disposed of by land application. A diagram of the geologic cross section showing well depths and screen intervals is presented in Figure 31.

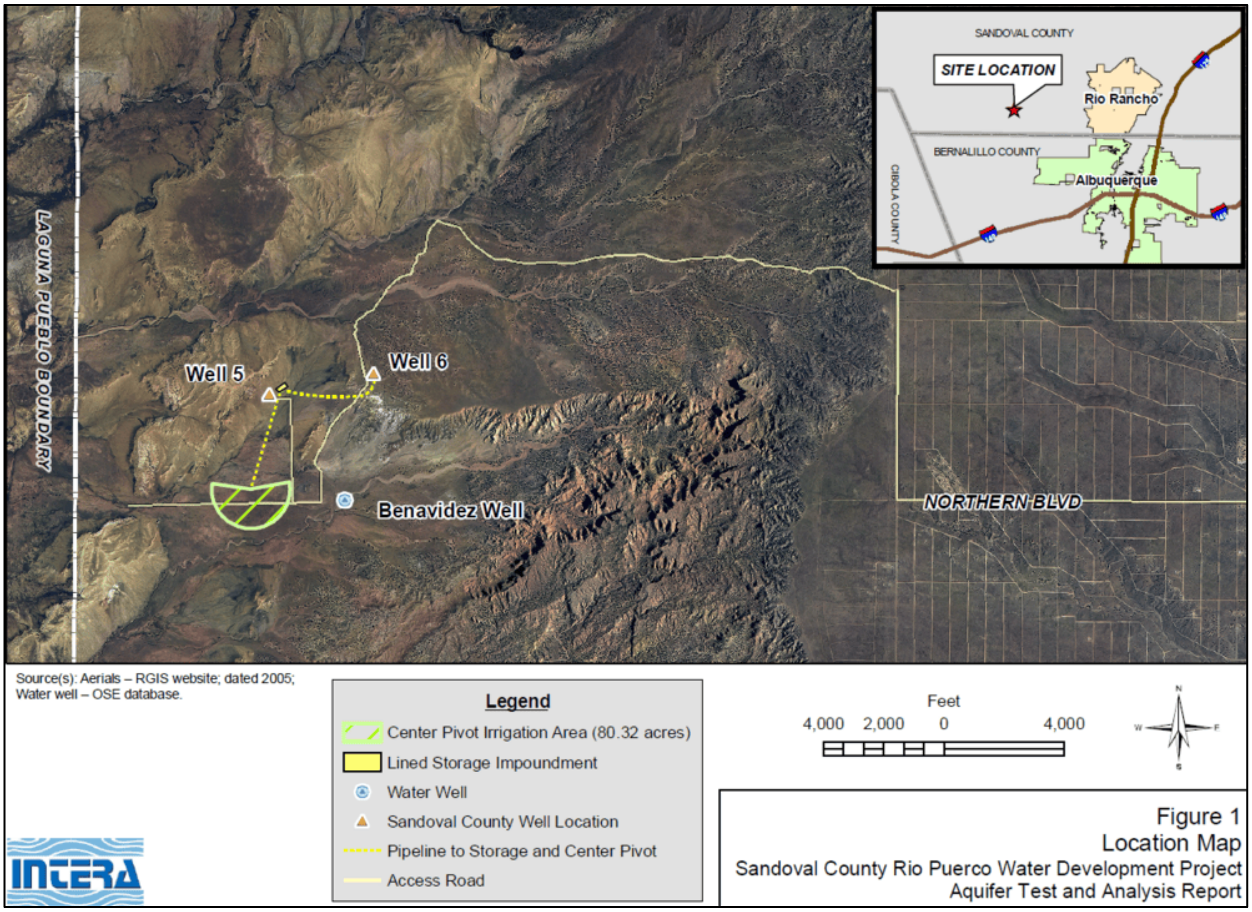

Figure 30. Location of the proposed Sandoval County Wholesale Water Utility project (INTERA Inc., 2008).

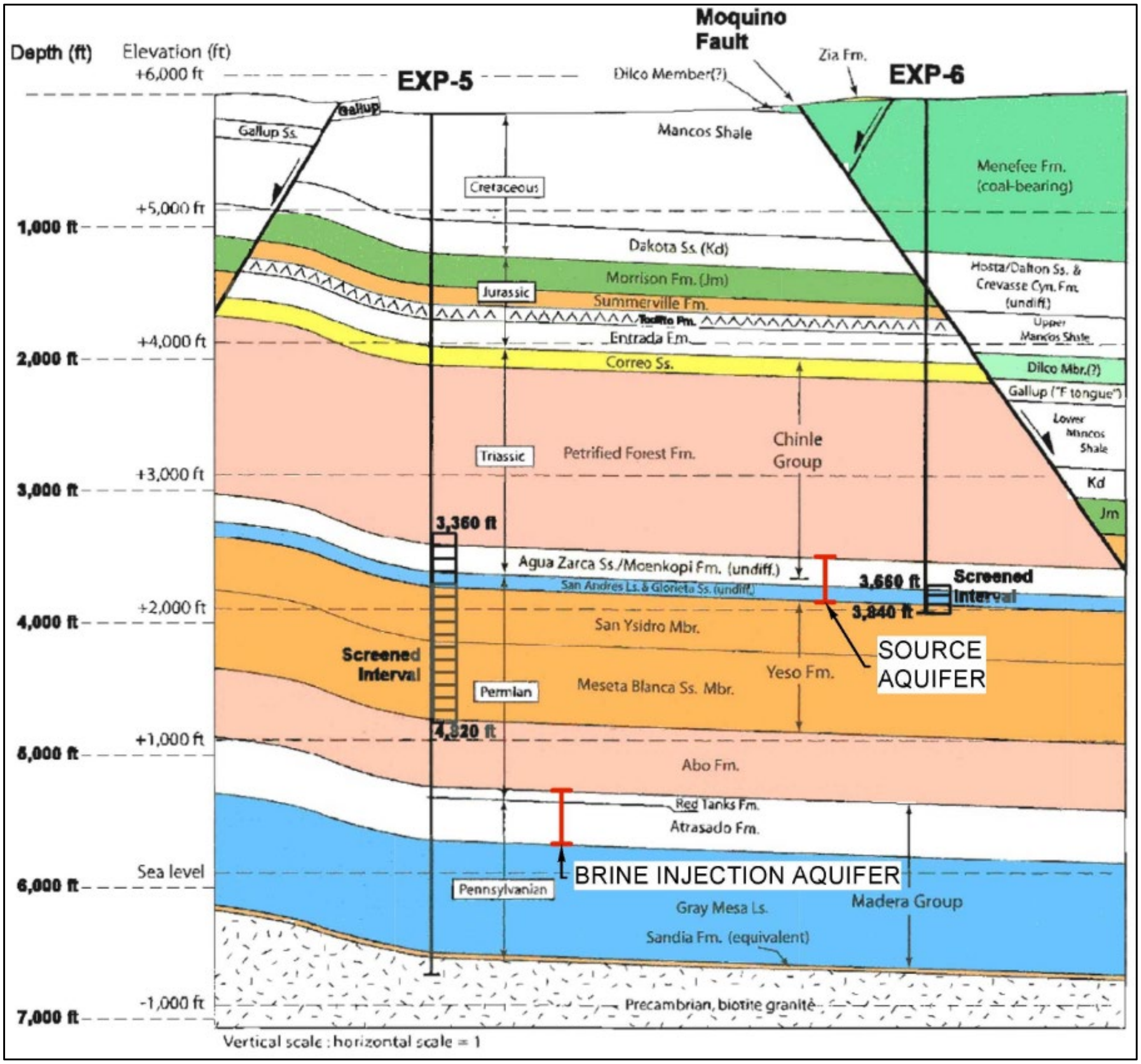

Figure 31. Geologic cross section and well depths for Well Exp-5 and Well Exp-6, Sandoval Co. Rio Puerco Water Development Project (Universal Asset Management, CDM, and INTERA, Inc., 2011, Appendix J).

The San Andres Limestone-Glorieta Sandstone aquifer (SAG), is a confined aquifer of average depth of about 3,500 ft (1,000 m) (see Figure 31). A 31-day aquifer test followed by a 60-day recovery period was done for well Exp-6 to determine hydrologic properties of the aquifer. Since the aquifer is under artesian conditions, pumping was not needed. The downhole pressure was monitored to determine aquifer response to the test. The well flowed at a rate of 150 gal/min (570 L/min) for 17 days and then for 250 gal/min (950 L/min) for the final 14 days. Two different methods for data analysis were done yielding two very different results for the storativity (S), namely, the amount of water released from storage per unit decrease in head. The total volume of water that can be recovered from the aquifer is based on the area (A) of the aquifer, the maximum drop in head (Δh) that can be achieved, and the storativity. For the Sandoval County project, the results are summarized in Table 12.

Table 12. Potential available groundwater supply for Sandoval County Wholesale Water Utility Project (INTERA Inc., 2008)

Parameter	**Analysis A**	**Analysis B**
Storativity (S)	6.92×10^{-4}	1.5×10^{-4}
Total Aquifer Capacity (S x A x Δh) (AF)	2.66×10^{6}	5.76×10^{5}
Years of Water Supply[1]	62	13

Notes:
[1]Years of supply at project demand of 43,200 AF/yr (53 M m^3/yr) (38 Mgal/d)

Note that the projected water demand of 43,200 AF/yr (53 M m^3/yr) is the supply of fresh water needed for a community with an ultimate population of 309,000 persons at build-out. A more proper estimate based on projected community growth rates is presented below.

The water quality from Well Exp-6 is summarized in Table 13 (Universal Asset Management et al., 2011). While the groundwater TDS was 12,000 mg/L, one third that of seawater, the high concentration of scale-forming constituents (i.e., calcium, magnesium, dissolved CO_2, and sulfate) will make desalination challenging. Furthermore, the presence of elevated concentrations of arsenic and radioactive constituents may make the desalination waste concentrate a mixed waste subject to hazardous waste regulations under RCRA and radioactive waste regulations administered by the Nuclear Regulatory Commission (NRC). The PER assumed that these wastes would be trucked to a low-level radioactive waste disposal facility in Texas.

A pilot treatment plant was constructed to desalinate the water from Well Exp-6 (Universal Asset Management et al., 2011, Appendix Q). The feed flow rate was 15 gal/min (57 L/min), which was designed to produce 12 to 13 gal/min (45 to 49 L/min) of desalinated water. There were several treatment challenges that had to be met by the treatment system. They included:

- Dissolved hydrogen sulfide (H_2S) and carbon dioxide (CO_2) should be removed to limit corrosion and help control pH
- All suspended solids must be removed prior to the RO system to prevent membrane fouling by particulates
- Hardness must be reduced to near zero to prevent scale formation on the membranes
- Arsenic and radionuclides must be removed to facilitate disposal or possible reuse of the RO concentrate
- Boron must be removed if the water is to be used for irrigation
- The feed water must be cooled to approximately 20°C to limit microbial growth and damage to RO membranes

Table 13. Summary of water chemistry from Well Exp-6. All concentrations in units of mg/L except as noted (Universal Asset Management et al., 2011)

Parameter	**Concentration**
Alkalinity (mg/L as $CaCO_3$)	1,800
Arsenic[1,3]	0.634
Boron[3]	9.7
Calcium	450
Carbon Dioxide	1,900
Chloride[2,3]	3,100
Fluoride[1,3]	4.8
Hardness (mg/L as $CaCo_3$)	1,500
Iron[2,3]	3.3
Lead[1,3]	ND
Magnesium	97
Phosphorous	0.29
Sodium	3,600
Silica	32
Strontium	8.8
Sulfate[2,3]	4,400
Thallium[1,3]	0.007
Uranium[1,3]	0.002
TDS[2,4]	12,000
Temperature (°C)	65
pH (pH units)[1,3]	7.05
Gross Alpha (pCi/L)[1]	209
Radium 226 + 228 (pCi/L)[1,3]	85

Notes:
[1]Regulated under the SDWA as a primary drinking water standard
[2]Regulated under the SDWA as a secondary drinking water standard
[3]Regulated under the New Mexico groundwater standards (20.6.2 NMAC)
[4]Regulated for groundwater used as domestic water supply (20.6.2.3103 NMAC)

Briefly, the treatment process consisted of: pre-treatment to remove suspended solids, dissolved gases, and adjust the pH for degasification; addition of caustic soda to remove hardness ions (Ca and Mg); granular media filtration to remove suspended solids; ion exchange to remove residual Ca and Mg ions; and finally, RO to desalinate the water. A process flow diagram is presented in Figure 32.

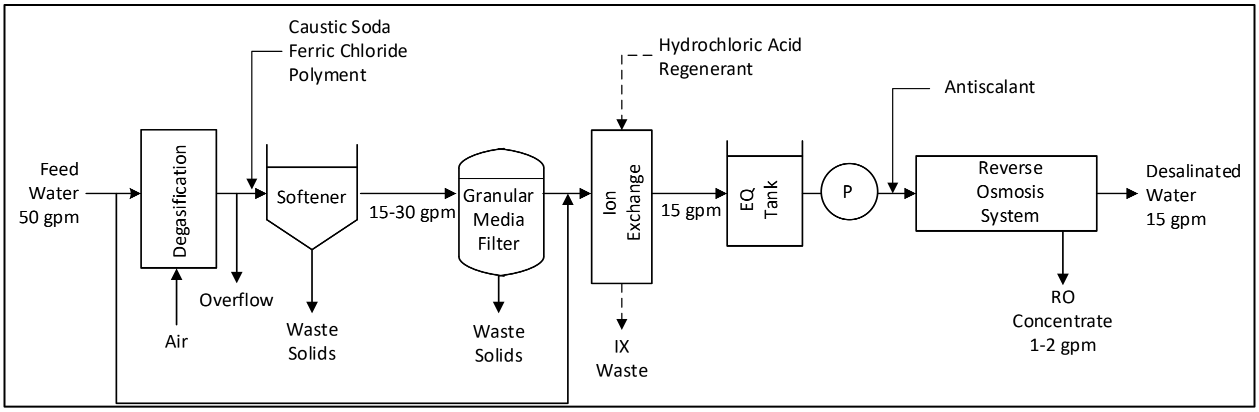

Figure 32. Process flow diagram of the desalination treatment system used for the Sandoval County Desalination Pilot Project (adapted from Universal Asset Management et al., 2011, Appendix Q).

The pilot treatment plant was operated for just over two months during which time the system operated at an overall feed water recovery ranging between 65% and 90% with an overall average recovery of about 75%. The system performed well although technical problems limited the treatment plant operation to less than 350 hours over the testing period. In part this reflects the difficulty of desalinating hard brackish groundwater in contrast to seawater. During the testing, the plant produced a TDS of the permeate that was typically around 150 mg/L and the water met all SDWA criteria.

The results of the pilot test and the hydrogeologic studies were used to prepare a preliminary engineering report (PER) to develop design criteria for a full-scale project to include estimates of capital and operating costs (INTERA, Inc. and WHPacific, 2008). The PER assumed high and low community growth rates in which the ultimate build-out to a population of 309,500 would occur in 50 and 70 years, respectively. Water supply and desalination treatment would be provided in increments of 5 Mgal/d (19,000 m^3/d). The PER provided cost estimates of a 5 Mgal/d (19,000 m^3d) plant as shown in Table 14.

These costs are based on construction and operation of fourteen 4,000 ft (1,200 m) deep wells each with a 500 gal/min (1,900 L/min) capacity, and trunk lines to deliver water to the treatment plant, cost of the treatment plant, management and disposal of desalination wastes, and pumping treated water to the top of the escarpment. The PER assumed 80% feed water recovery so that a 6.25 Mgal/d (24,000 m^3/d) treatment plant would be needed to provide 5 Mgal/d (19,000 m^3/d) of fresh water.

Table 14. Estimated life-cycle costs for brackish water facilities to produce, treat, and deliver 5 Mgal/d of fresh water in western Sandoval County, New Mexico (2008 dollars, 6% interest rate) (INTERA Inc. and WHPacific, 2008)

	Capital Cost			**Annual OM&R[1] Cost**		**Combined OM&R[1] and Debt Service**	
Description	Total	Annual	$/1000 gal	Total	$/1000 gal	Total	$/1000 gal
Brackish water production and transport	$72,380,000	$6,310,000	$3.46	$435,000	$0.24	$6,745,000	$3.70
Desalination	$43,500,000	$3,790,000	$2.08	$2,566,000	$1.40	$6,346,000	$3.48
Waste solids and brine handling	$14,980,000	$1,310,000	$0.72	$811,000	$0.44	$2,121,000	$1.16
Potable water delivery to escarpment	$11,981,000	$1,040,000	$0.16	$94,000	$0.05	$1,134,000	$0.21
Total Estimated Cost	$143,000,000	$12,450,000	$6.42	$3,906,000	$2.13	$17,866,000	$8.55

Notes:
[1]OM&R – operation, maintenance and replacement

Several issues should be noted regarding this project. First, the volume of the water available for the project is based on an aquifer area of 2,000 mi^2 (5,200 km^2), extending from near the western city limits of Rio Rancho to the eastern flank of Mt. Taylor, and from the San Juan County line on the north to Interstate-40 on the south. The volume is also based on drawing down the head in the aquifer (Δh) 3,000 ft (910 m). The expected life of the water supply does not consider demand for other projects in the basin for which there are hundreds of nearby Notices of Intent (NOIs) to divert deep brackish groundwater (Table 7 and Figure 14). Much of the aquifer that would be impacted by this project is under lands owned by Native American Pueblos. The regulatory and institutional consequences of large drawdowns and groundwater impacts from deep aquifer depletion under Indian lands are not known.

Second, in order to provide 43,200 AF/yr (53,000,000 m^3/yr) of fresh water at build-out, the annual pumping requirements will be 54,000 AF/yr (67,000 m^3/yr) assuming 80% feed water recovery from the desalination plant. This will require drilling 95 wells capable of delivering flows of 500 gal/min (1,900 L/min). The wells would be placed on half-mile spacing and require many miles of large diameter pipelines from the wells to the treatment plant and then back to the salt water disposal wells.

Third, desalination will generate 10,800 AF/yr (9.6 Mgal/d, 13,000,000 m^3/yr) of RO concentrate waste requiring disposal. While it may be possible to recover commodities from some of this waste, this has not been demonstrated at other inland desalination plants. Therefore, it is likely that RO concentrate will be disposed of by deep well injection in salt water disposal wells. These will be deeper and more costly than the brackish water production wells. Note that the cost estimates for waste management summarized in Table 14 are roughly one-third the capital and operating costs of the treatment plant itself. If the waste is classified as hazardous and/or radioactive, the management and disposal costs will be greater.

Fourth, the projected costs for desalinated water are high, approximately double the cost of water currently delivered to customers served by the City of Rio Rancho when adjusted for inflation (Rio Rancho, 2025). Costs not included in this analysis include those for the fresh water distribution and storage system, which will add to the cost of water delivered to the customers.

One potential consequence that was not considered in the studies supporting this project is the effect that very large declines in hydrostatic head (3,000 ft or 900 m) will have on the physical properties of the aquifer. Reducing the pore pressure in the formation will cause aquifer compaction and potential subsidence that might reach the land surface. Deep aquifer compaction may also increase leakage from overlying formations as a result of upward fracture migration (NMED and ERG, 2024).

Figure 33 presents projections of the groundwater pumping rates for high and low growth rate scenarios and also the total volume of groundwater pumped since the beginning of the project. The growth rate scenarios were estimated by INTERA Inc. and WHPacific (2008). The total volume of fresh water delivered for water supply will be 43,200 AF/yr (53,000,000 m^3/yr) at build-out, which includes 12,000 AF/yr (14,800,000 m^3/yr) of water delivered to the City of Rio Rancho. The desalination plant is assumed to operate at 80% recovery so that at build-out, the total annual volume of groundwater pumped will be 54,000 AF/yr (67,000,000 m^3/yr). Figure 33 also plots the upper and lower total estimates of the volume of the aquifer, 2,660,000 and 576,000 AF respectively. The lower and upper lifetimes of the proposed project occur when the cumulative volume of water pumped from the aquifer (black lines) exceeds these two estimates (red lines).

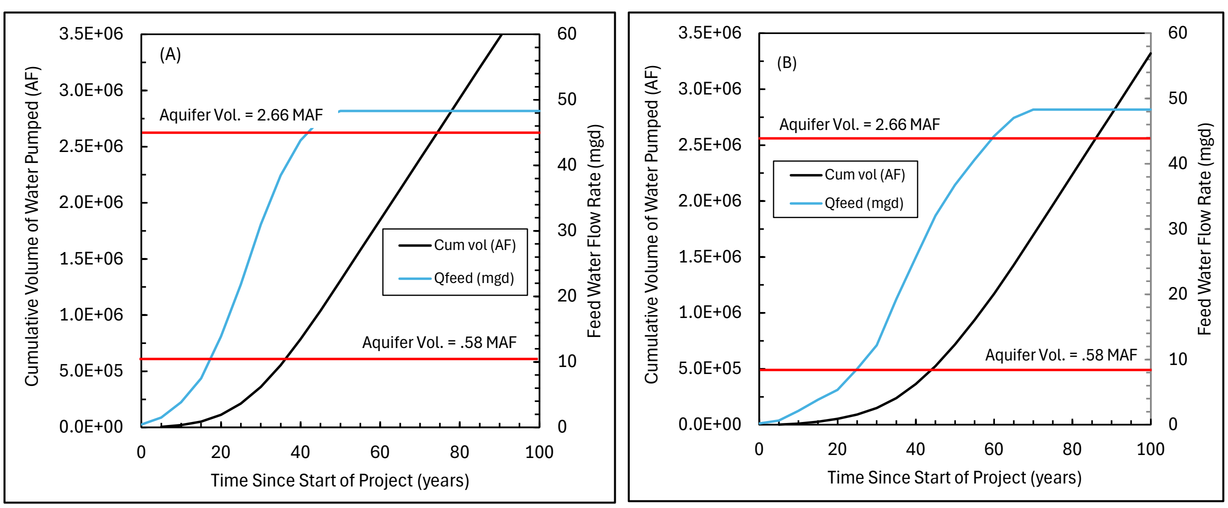

Figure 33. Comparison of brackish water pumping rates and total volume of water pumped for (A) the high growth rate scenario and (B) low growth rate scenario. The red lines represent the high and low estimates of the volume of recoverable groundwater. Data from INTERA Inc. and WHPacific (2008).

The information plotted in Figure 33 illustrates the greatest concern with this proposed project, namely, the water supply is not sustainable. The life of the water supply primarily depends on two factors, the rate of growth in the community and volume of recoverable water assumed to be in the aquifer. Under the high growth scenario (Figure 33 (A)), the aquifer can provide water for between 35 years if the recoverable volume is 576,000 AF or 75 years if the volume is 2,660,000 AF. Under the low growth rate scenario (Figure 33 (B)), the life of the project varies between 45 years and 85 years. Whether the life of the project is 35 years or 85 years, this analysis raises an extremely important policy question: What will the community of 309,500 people use for its water supply when the deep brackish groundwater resource is depleted?

The estimated life of the water supply presented above was based on hydrogeologic data from two wells located near each other. There is no reason to believe that they represent a reliable average over the entire area of the planned development. It is further based on the assumption that the aquifer was completely confined, that there were no other diversions from the aquifer, and that the aquifer had no hydrologic connection to shallower aquifers or surface water so that it did not impact these resources.

The hydrologic model by Jones et al. (2013) and summarized by Shomaker (2014) found that deep aquifer development in the Rio Puerco Basin will measurably deplete surface water resources by leakage from overlying formations and infiltration along the basin boundaries, an impact that will require acquisition of surface water rights to offset this depletion. An additional factor, not considered in the analysis presented here is that the production rate of the deep wells will decline as the piezometric head in the aquifer drops. This will require constructing additional wells to produce the desired volume of water (Jones et al., 2013).

Conclusions and Recommendations

There has been much interest in development of brackish groundwater resources in New Mexico for two reasons. First, crude estimates of the water suggest that the volume of recoverable water is very large, perhaps as much as 3 billion acre-feet. Second, until 2009 deep brackish groundwater was not subject to jurisdiction by the New Mexico OSE; anyone could recover and use it simply by submitting a Notice of Intent (NOI) to drill a well and extract groundwater for use without obtaining a water right. This lack of jurisdiction led to the filing of more than 700 NOIs, although only 31 deep brackish groundwater wells have actually been drilled to date, mostly to produce water for the oil and gas industry.

A review of the hydrogeology of deep brackish aquifers in regions of the state where new water is needed to support municipal and industrial growth shows that little information on the quantity or quality of these resources is available, primarily because the cost of quantifying a resource that, until recently had little or no value as a water supply, has seldom been estimated quantitatively. Thus, much of the interest in deep brackish groundwater is based on speculation and conjecture.

This review described one well-done and well-funded investigation for a large deep brackish groundwater project to supply fresh water for a large development approximately 20 miles northwest of Albuquerque (Universal Asset Management, et al., 2011). Two deep wells were drilled, an aquifer test was done to characterize the resource, a 15 gal/min (57 L/min) pilot desalination plant was constructed and operated for over two months, and a preliminary engineering report (PER) was prepared to develop design criteria and preliminary cost estimates for a water supply project. This project serves as a model of the type of investigation needed to evaluate a proposed deep brackish groundwater project and illustrates many of the challenges that such a project will face.

The review presented here illustrates the following several major challenges that must be addressed to support development of deep brackish groundwater supplies. Many of these needs and concerns have also been identified in a study by NMED and ERG (2024).

Characterize and Quantify the Resource: Before any project to develop brackish groundwater resources are proposed, the hydrogeologic characteristics and water quality of the aquifer must be determined. This should include:

- Determine the aquifer's hydrogeological properties over the lateral and vertical extent of the aquifer (hydraulic conductivity, storage coefficient, barriers to flow such as faults and intrusions, leakage to/from overlying formations, and possible impact on surface water sources)
- Construct a three-dimensional flow model of the formation to quantify production, impacts on overlying formations and recharge from the basin boundaries, and impacts from nearby groundwater pumping
- Identify other proposed developments that will divert groundwater from the same deep aquifer as this information is needed to estimate the life of the proposed project
- Assess groundwater quality including presence of scale forming as well as hazardous, and radioactive constituents that will affect desalination processes
- Identify how desalination wastes will be disposed of and if they will be disposed by deep well injection, identify and characterize the formation and determine if there are risks from induced seismicity
- Determine the life of a deep aquifer groundwater supply and how its production rate will vary over the lifetime of the project
- Determine whether enough suitably located well sites are available
- Determine whether pipeline and utility rights-of-way are available
- Identify how issues associated with impacts that very large drawdowns underneath lands owned by others will be addressed

Develop Design Criteria and Preliminary Cost Estimates for Brackish Water Recovery: In order to determine the feasibility of implementing a brackish groundwater supply, the method of recovering the water must be identified. This will involve using a groundwater model to determine the number of wells, their depth and pumping rate, their spacing, and surface infrastructure needed to deliver water to a desalination plant as well as to deliver fresh water to the proposed community.

Develop Design Criteria and Preliminary Cost Estimates for A Brackish Water Desalination Plant: It is important to recognize that desalination of brackish groundwater is very different and more challenging than desalinating sea water due to the complex water chemistry, the frequent presence of hazardous and radioactive constituents in the feed water, and the lack of options for disposing of desalination wastes at inland locations. The design for a desalination plant must recognize these challenges, identify how they will be met, and develop capital and operating cost estimates for the treatment plant. The source of energy for pumping from deep wells and desalination must be identified.

Characterize the Wastes from the Desalination Process and Determine How They Will Be Managed: Management and disposal of wastes from a desalination process are especially challenging in New Mexico because the only viable disposal option in most locations is disposal by deep well injection. The volume of wastes to be injected, the depth and design of the injection well(s), and the underlying geology must be taken into account to evaluate the risk of induced seismicity. If the wastes have high concentrations of hazardous or radioactive constituents that are regulated under hazardous or radioactive waste regulations, identification of handling and disposal methods will be especially important.

Identify the Lifetime of the Project and How Water Demand Will Be Met Once the Deep Aquifer Has Been Depleted: The example presented of the proposed Sandoval County Wholesale Water Utility illustrates the biggest technical challenge presented by developing deep brackish groundwater resources – the resource is not sustainable. Therefore, any project intending to use this resource should be required to identify the life of the project and how demand for water will be met after the aquifer has been depleted. In order to determine the life of the water supply, it will be necessary to identify other projects tapping into the same aquifer and determine the cumulative impact on the resource.

Whether a future source of water is required once the aquifer is depleted may depend on the nature of the proposed project. For example, the need for water for a private or industrial project for agricultural or industrial use may not require identifying a sustainable supply because there are limited public consequences of the project ending when the supply runs out. However, if the water is intended to supply a residential or municipal development, the consequences of running out of water are much more severe. In these cases, identification of a sustainable source of supply is critically important.

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Produced Water from Oil and Gas Development

Introduction

New Mexico is the second largest producer of oil and gas (O&G) in the U.S. (EIA, 2024) and water is closely connected to exploration and development of these resources. Major uses of water are for drilling, hydraulic fracturing (fracking), processing and refining, and for dust control. The sources of wastewater generated by the O&G industry include wastewater from processing and refining operations, sanitary wastewater from bathrooms and showers, stormwater runoff, and wastewater brought to the surface during oil and gas extraction, which is referred to as produced water (PW). Produced water presents a special challenge because of the enormous volume generated and its very high salinity. The total volume of PW generated in New Mexico in 2024 was 324,000 AF (400,000,000 m^3), with greater than 98% of this water coming from the Permian Basin of southeastern New Mexico (NMOCD, 2025). The average salinity of the Permian Basin PW was nearly 129,000 mg/L (Jiang et al., 2022b) compared to the salinity of seawater, which is about 35,000 mg/L. An additional factor is that PW is produced from over 50,000 widely dispersed O&G wells (NMOCD 2025) and is transported around the basin by fleets of large trucks that create traffic problems and damage roads, and by an intertangled network of temporary and permanent hoses and pipes that are vulnerable to leaks.

The volume of PW generated is directly correlated to O&G production that has grown almost exponentially in the past 10 years in New Mexico. Currently, use of this water outside of the O&G industry is not allowed so that virtually all of it is disposed of by subsurface injection into deep salt water disposal (SWD) wells. However, the very large annual volume of water generated suggests that with appropriate treatment it could be a major source of water to augment existing supplies. In fact, PW has been specifically identified as a source of new water for future development in the state's 50-Year Water Action Plan (Grisham, 2024; NMED and ERG, 2024).

Although PW has been generated by O&G production since inception of the industry, until recently, little knowledge had been developed about its quality or whether it could be treated for reuse; it was simply a waste product that could easily and inexpensively be disposed of by deep well injection. In the last 10 or 15 years, discovery of the correlation between deep well injection of PW and induced seismicity (i.e., increased occurrence of earthquakes) has brought increased scrutiny to management of this waste. At the same time, recognition of its potential for reuse has generated substantial research into its quality along with development of treatment technologies (NAS, 2017). This section provides a brief review of recent research and development on the chemistry, treatment, and potential reuse of PW. The focus is on information relevant to the challenges in New Mexico and primarily those in the Permian Basin. Much less information is available for PW from the San Juan Basin of northwestern New Mexico, which produces far less water and which has much lower salinity. The regulatory issues pertaining to PW treatment and reuse are also discussed as they have bearing on treatment, waste disposal, and potential reuse options.

Sidebar Discussion – Water Use for Fracking Operations

Hydraulic fracturing, commonly referred to as fracking, involves the injection of large volumes of water under high pressures to create fractures of the rock in deep formations in order to increase its permeability and consequently the amount of O&G that can be recovered. Fracking was first developed in the 1860s to increase productivity of water wells through use of explosives to fracture the rock., Hydraulic fracturing by the O&G industry began in 1949 and has been used extensively ever since (AO&G, 2024). Fracking has been widely used for improving production of conventional water and O&G wells, where "conventional" refers to vertical wells. Figure 34 is a diagram illustrating the general types of O&G resources and illustrates the types of wells used to recover them (EPA, 2016a, 2016b).

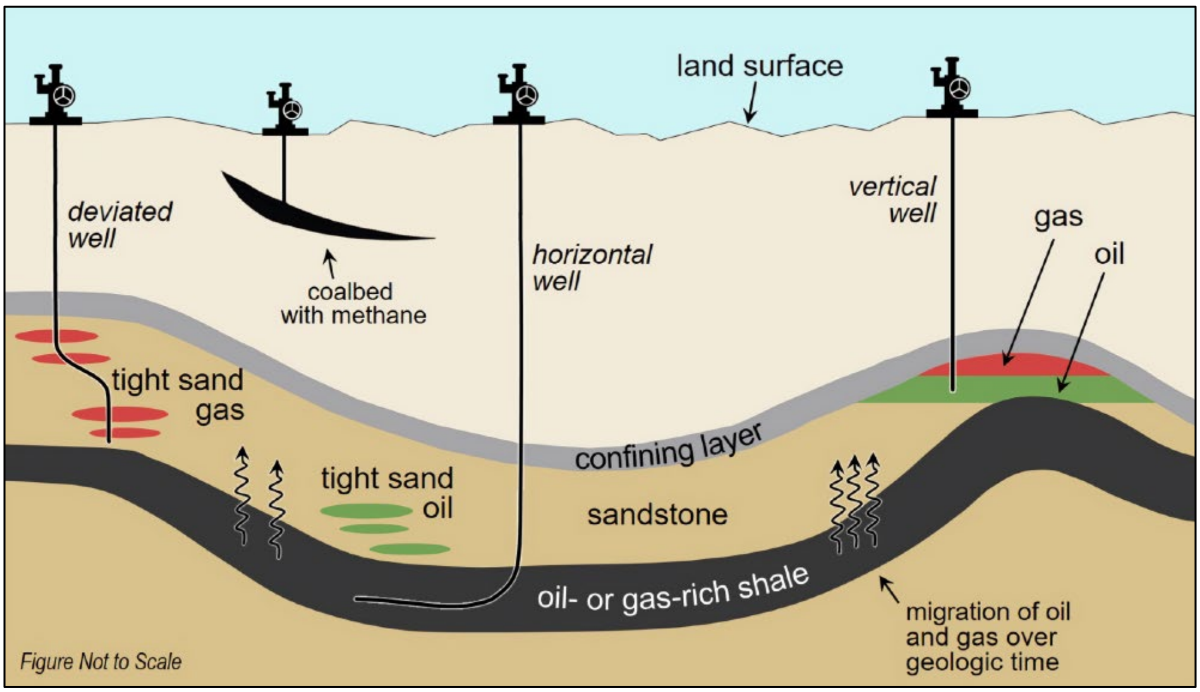

Figure 34. Schematic of general types of oil and gas resources and the orientations of production wells used in hydraulic fracturing (EPA, 2016a and 2016b).

In the 1980s, the drilling industry began experimenting with use of horizontal drilling methods to allow recovery of O&G from low permeability tight sand and shale formations. These wells were then fracked to increase their production (AO&G, 2024). Horizontal wells drilled into these tight formations are referred to as unconventional wells. Horizontal wells are widely used in the Permian Basin with an average horizontal length of 10,000 ft (3,000 m) and maximum horizontal length in excess of 21,000 feet (6,300 m) (EIA, 2022).

A variety of chemicals may be added to the slurry to facilitate and improve the fracking process (see Table 1). A summary of the characteristics and function of the major additives has been provided by EPA (EPA 2016a, EPA 2016b) and King and Durham (2017):

- Proppant (sand or ceramic grains): Holds fractures open after the high pressure used to fracture the rock is relaxed
- Friction reducer: Used to reduce fluid friction to reduce pumping pressure at the high velocities used in slickwater fracks
- Disinfectant (biocide): Added to prevent microbial growth that can plug formations and contribute to microbially induced corrosion of the well casing
- Surfactants: Added to modify surface or interfacial tension, break or prevent emulsions, and create foam if a gas such as N_2 is used in fracking
- Gelation chemicals (thickeners): Guar gum and cellulose polymers may be added to keep proppant in suspension
- Scale inhibitors: Phosphates or phosphonates will reduce formation of mineral scaling by compounds such as calcite ($CaCO_3$) and gypsum ($CaSO_4$)
- Hydrochloric acid: Acid is sometimes used to dissolve some minerals, especially carbonates, and for pH control
- Corrosion inhibitor: If acid is used in the frack fluid, corrosion inhibitors may be added to prevent corrosion of iron and steel in the well casing and pipe

FracFocus (www.FracFocus.org) is a national registry of the chemicals used in fracking and is managed by the Ground Water Protection Council. FracFocus maintains an extensive compilation of the chemicals used in fracking and their CAS Registry Numbers, which can be used to identify their chemical characteristics. Most of the chemicals used have little or no toxic or hazardous characteristics. In New Mexico, drillers are required to report the chemicals used in each fracking operation to FracFocus, as part of their well completion report (19.15.16.19 NMAC), and this information is available to the public. This is analogous to U.S. Food and Drug Administration regulations that require a listing of all of the ingredients on food containers although not the actual recipe. Note that New Mexico regulations prohibit the use of per- or polyfluoroalkyl substances (PFAS) in completion of O&G wells (NMAC 19.15.7.16). The general composition of a typical fracking solution is given in Table 15 (FracFocus, 2024).

Table 15. Composition of typical fracking fluids (FracFocus, 2024)

Ingredient	Concentration (%)
Water	85.02
Proppant	14.20
Gelling agent	0.5
Acid	0.07
Corrosion inhibitor	0.05
Friction reducer	0.05
Clay control	0.034
Crosslinker	0.032
Scale inhibitor	0.023
Breaker	0.02
Iron control	0.004
Biocide	0.001

The volumes of water required for fracking vary considerably due to the length of the well, formation characteristics, and the type of fracking fluid used. In the past, the industry used gel-based fluids in which a gelling agent was added to keep the proppant in suspension. In recent years, the industry has turned to slickwater fracking, in which very high fluid velocities are maintained to keep the proppant in suspension and little or no gelling agent is added (Ely et al., 2014; Norris et al., 2016). Hydraulic fracking of wells requires a very large volume of water that depends on the type of well (conventional or horizontal), length of the fracking zone, formation characteristics, and frack fluid additives. Gallegos and Varela (2016) report that the median volume of frack fluid for horizontal wells was 3 Mgals (11,000 m^3) and ranged up to 11 Mgals (41,000 m^3).

Fracking has received a lot of negative national attention due to: (1) the very large volumes of water used and consequent impacts on nearby fresh water supplies, (2) the large number of chemical additives used and public perception of the hazards they present, (3) poor management of return flows from the fracking process in some basins, and (4) concern about induced seismicity from the fracking process. This side-bar discussion addresses the source of water used for fracking. As noted above, information on chemical additives is available from FracFocus (2024). Return flow of frack fluids, known as flowback, is managed along with PW in most O&G operations. Produced water management and disposal is described briefly in this chapter. While induced seismicity has been linked to fracking operations in other basins, it is associated with few earthquakes in the Permian Basin; earthquakes in the Permian Basin are primarily caused by deep well injection of PW in salt water disposal (SWD) wells (Schultz et al., 2020; Skoumal and Trugman, 2021; Skoumal et al., 2020).

Until 2019, there was no reliable information on the source of water used for fracking. Fresh water was often used, which generated a commercial market near oil fields in which water rights holders sold large volumes of water to drillers for use in fracking. Acquisition of water was not well regulated; therefore, the source and quantity of water used for fracking was largely unknown. In 2019, the New Mexico Oil Conservation Commission (NMOCC) adopted new regulations (19.15.16.21 NMAC) requiring the reporting of the source of water used for fracking by breaking it into one of four categories: PW, fresh water (TDS < 1,000 mg/L), brackish water (1,000 mg/L < TDS < 10,000 mg/L), and saline water (TDS > 10,000 mg/L). New Mexico began requiring the reporting of the source of water used for fracking in October 2020. The monthly volumes of water used for fracking since then are plotted in Figure 35 and show that average water used for fracking in 2024 consisted of 60.8% PW, 3.8% fresh water, 18.9% brackish water, and 17.5% saline water.

Slickwater fracking uses little or no gelling agents to keep the proppant in suspension. Instead, very high velocities of up to 100 ft/sec (30 m/sec) are used at a flow rate of 100 bbl/min (16,000 L/min) (Yang et al., 2019; Nguyen et al., 2018; Palisch et al., 2010). To overcome the extremely high friction losses produced by these velocities, friction reducers are added. Friction reducers include natural polysaccharides such as hydroxypropyl guar, guar gum, xanthum gum, polyethylene oxide, and more recently, polyacrylamide polymers (Yang et al., 2019). Use of friction reducers can reduce friction losses in fracking slurries by up to 50%.

Traditional friction reducers did not work in high salinity solutions because the long chain polymer molecules would curl or clump (Yang et al., 2019). Recent development of friction reducers that are compatible with the highly saline PW solutions has allowed the industry to use PW as well as saline and brackish water instead of fresh water (Li et al., 2016). These waters, and especially PW, are much cheaper and more readily available than fresh water, Furthermore, there is some evidence that fracking with high salinity solutions produces better recovery of O&G because the chemistry of the frack fluid is more compatible with the formation water.

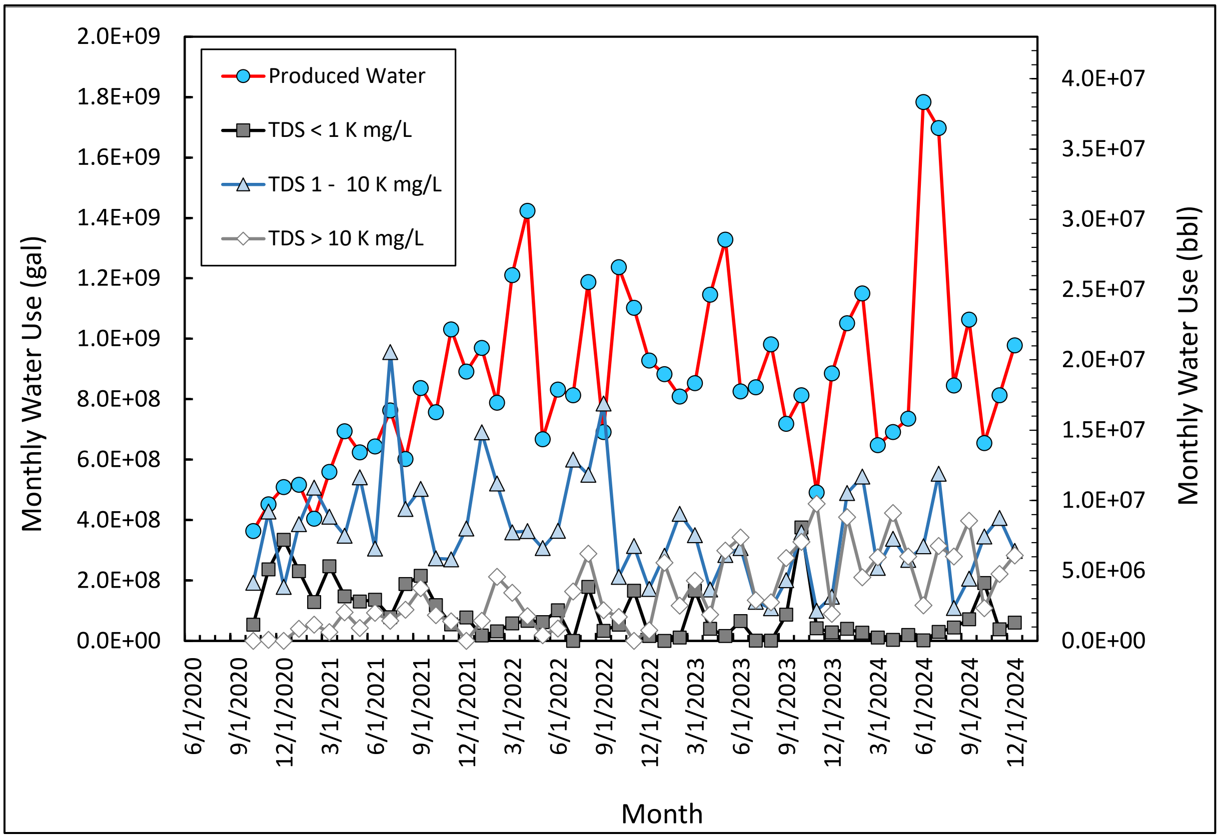

Figure 35. Monthly volumes of sources of water used for hydraulic fracturing in New Mexico (NMOCD data).

Reuse of PW for fracking requires that it be treated in order to prevent damage to the formation. Treatment generally consists of removal of oil, suspended solids, and dissolved iron; disinfection and the addition of biocides to prevent microbial growth, particularly of sulfate reducing bacteria; pH adjustment; and addition of corrosion and scale inhibitors (Eyitayo et al., 2023a). Similar treatment is required if PW is used for enhanced oil recovery (EOR). Note that PW desalination is not required for its use as a fracking fluid although chemical additives are often included to reduce corrosion and prevent biological growth from clogging the formation.

The data reported to the New Mexico OCD on the source of water used for fracking shows that in recent years, the use of fresh water for fracking is a very small fraction of the total volume. Furthermore, required reporting of chemical additives to a publicly available clearinghouse supports the claim that the chemical hazards of frack fluids are much less than is commonly perceived by the public.

The discussion presented here is not intended as an argument in favor of fracking to support O&G development. Rather it is meant to improve the understanding of the technical issues underlying the current regulations governing fracking, and to a lesser extent, potential reuse of PW. Note that water used for fracking returns to the surface as a mixture of flowback and formation water in a few weeks or months, so use of PW for fracking does not constitute a disposal method.

Regulatory Considerations

Reviews of the regulations pertaining to discharge and disposal of PW have been published by Jiang et al. (2022a) and the Ground Water Protection Council (GWPC 2019, 2023). These reviews describe the regulatory challenges that pertain to PW reuse, summarize existing PW reuse outside of the O&G industry, and identify research needs to make beneficial reuse safer. It is important to make the distinction between recycling consisting of reuse within the O&G industry, and reuse outside of the industry. The federal and state regulations governing PW treatment, disposal, and reuse in New Mexico are briefly summarized below.

Federal Regulations: Federal laws that may have jurisdiction over PW include the Clean Water Act (CWA) and the Safe Drinking Water Act (SDWA). The CWA provides jurisdiction over discharges of treated water to surface waters of the United States, commonly abbreviated as WOTUS. The definition of WOTUS currently does not include ephemeral streams or playa lakes. The CWA establishes a permit program for discharges to WOTUS known as the National Pollutant Discharge Elimination System (NPDES). Effluent limitations guidelines (ELG) have been established for PW discharges west of the 98th meridian (approximately the longitude of Dallas, Texas) (40 CFR part 435). These regulations address discharges from all O&G point sources including PW, drilling fluids, and well treatment fluids. The only criterion for PW discharge is that a best practicable control technology must be used, which achieves a 30-day average maximum concentration of oil and grease of 48 mg/L and a maximum one-day concentration of 72 mg/L (EPA, 2020). More stringent criteria are determined for subsequent reuse of the treated PW, which are generally addressed by state regulations. Legislation passed in 2025 (NMSA 74-6-2) allows New Mexico to develop and administer its own surface water discharge permit program that may eventually extend to discharge of treated PW. This will require development of state regulations and identification of a mechanism to fund the permit program.

The SDWA assigns EPA authority for establishing underground injection control (UIC) regulations. There are six classes of UIC wells: Class I for industrial and municipal waste disposal, Class II for injection wells disposing of O&G fluids, Class III for injection wells for solution mining, Class IV govern disposal of hazardous and radioactive wastes, Class V for wells for injection of non-hazardous wastes into formations that are above or contain underground sources of drinking water, and Class VI for injection wells used for geologic sequestration of CO_2. The regulations allow states to regulate Class II UIC wells if they can demonstrate the authority and ability to properly manage the program; this is known as primacy. The NMOCD has primacy for permitting and supervising operations of Class II wells for disposal of O&G wastes. The EPA recently announced its intention to develop effluent limitations guidelines to permit discharge of treated PW to surface waters in recognition of new treatment technologies and management strategies (USEPA, 2025c), however, a timeline for issuance of these guidelines was not revealed.

In addition to the regulatory programs, EPA has created the National Water Reuse Action Plan (NWRAP) to encourage reuse of municipal, industrial, and other types of wastewater including PW (EPA, 2025a). In addition to summarizing regulatory programs for PW reuse, the NWRAP has compiled specifications needed to be met according to the intended reuse of treated PW, referred to as “fit-for-purpose” criteria.

One consideration that may affect treatment and reuse of PW and disposal of waste products from the treatment process is that they will likely have characteristics of hazardous waste and radioactive waste. Subtitle C of the Resource Conservation and Recovery Act (RCRA) provides an exemption for wastes from O&G exploration and production, which means that PW is not considered a hazardous waste and is not subject to this law. This is an important exemption because PW generally has many constituents that exhibit hazardous characteristics at high concentrations as defined under RCRA. EPA guidance (EPA, 2002) states that the exemption applies to “drilling fluids, produced water, and other wastes associated with the exploration, development or production of crude oil or natural gas.” “Constituents removed from produced water before it is injected or otherwise disposed” are included in this exemption, which means that residuals from PW treatment are not considered a hazardous waste provided the treatment process, treated water, and wastes remain under the control of the O&G industry. If treatment or reuse of the water is done by entities outside of the industry, this exemption may no longer be applicable. This is an unsettled legal question in New Mexico that may affect the feasibility of reusing treated PW outside of the industry.

Produced water also has high concentrations of radium, uranium, and other radioactive constituents. Treatment of PW for reuse will further concentrate these elements and greatly increase their concentration in desalination plant wastes. These wastes will be classified as technologically enhanced naturally occurring radioactive materials (TENORM). EPA has recognized the health risks associated with TENORM from O&G wastes but has not developed standards for management of this waste (EPA, 2025b).

Regulations in Other States: The Groundwater Protection Council (GWPC) has summarized state regulatory programs pertaining to PW reuse for 14 O&G producing states. A very brief summary of the regulatory programs in Colorado, Texas, and New Mexico is provided in this section. More details are provided in the GWPC reports (GWPC 2019, 2023) and the analysis by Jiang et al. (2021).

Produced water in Colorado falls under the jurisdiction of the Colorado Energy & Carbon Management Commission of the Colorado Department of Natural Resources. The Commission has developed guidance for PW sampling and analysis, water demands for fracking, and evaluation of aquifer exemption criteria for Class II UIC wells. The Colorado Department of Public Health and Environment has primacy for administering the NPDES surface water discharge program. Produced water has not been used outside of the O&G industry in Colorado. The Colorado Produced Water Consortium (COPWR, 2024) has been tasked with identifying methods to evaluate PW analytical and treatment methods to determine its potential for use outside of the O&G industry by July 1, 2025 (COPWR, 2024). A more complete discussion of state regulations governing PW management is available from this source.

The Railroad Commission of Texas has jurisdiction of natural resources and regulates the UIC program and PW reuse within the O&G industry. The Texas Commission on Environmental Quality (TCEQ) has authority over Class V disposal wells, the NPDES surface water discharge program, and land application of treated wastewater (TCEQ, 2025). A recent news article (Pskowski and Baddour, 2024) reported that several applications have been filed to discharge large volumes of treated PW to surface waters in West Texas. The discharge volumes ranged from 650,000 gal/d (2,500 m^3/d) to 17 Mgal/d (64,000 m^3/d).

Recent legislation in Texas established a permitting program for commercial water recycling facilities and provides funding for development of PW treatment technologies, standards, and regulations by the Texas Produced Water Consortium. Permits for recycling may be authorized by the Director of the Railroad Commission on a case-by-case basis (16 TAC section 3.8(d)(7)). Jiang et al. (2021) briefly mentions a couple of small pilot studies in which land application of treated PW has been studied. In 2024, the Commission published a draft framework for conducting pilot studies of beneficial reuse of PW with the expectation that final rules will become effective July 1, 2025 (RRC, 2024).

<u>New Mexico Regulations:</u> The handling and disposal of PW generated in New Mexico is subject to regulation by the New Mexico Oil Conservation Division (NMOCD) within the state's Energy, Minerals, and Natural Resources Department (EMNRD) under the Oil and Gas Act (70 NMSA 1978). New Mexico passed amendments to the O&G Act in 2019, referred to as the Produced Water Act, which identified ownership, responsibility, and liability for PW when it is transferred to another operator. It clarified that PW is not associated with a water right administered by the State Engineer, and allowed NMOCD to assess penalties for violations of the O&G Act. In addition, the Produced Water Act amended the Water Quality Act (NMSA 74-6-2, 1978) and directed the state's Water Quality Control Commission (WQCC) to adopt regulations for treatment and reuse of PW. Until regulations have been adopted by the WQCC, the NMED has declared that no reuse of treated or untreated PW is allowed outside of the O&G industry. Regulations adopted by the WQCC under authority of the Water Quality Act established water quality criteria that must be met for domestic water supply, crop irrigation, and livestock watering and wildlife habitat (20.6.4 NMAC), which will likely apply to reuse of PW. A wastewater reuse rule was passed in 2025 that regulates pilot plants that treat PW; however, it prohibits reuse of this treated water outside of the O&G industry (20.6.8 NMAC).

The NMED regulates NORM in the O&G industry under 20.3.14 NMAC. This rule establishes exemptions for natural gas and gas products and crude oil and oil products. Produced water and waste residuals from treatment of PW may be exempt if the exposure levels are low near the surface of the tank or impoundment, or if the waste contains Radium-226 at less than 50 pCi/g or less than 150 pCi/g for any other NORM radionuclide. Produced water is exempt from state radiation standards if it is disposed in Class I or Class II UIC wells or stored in an approved double-lined pond. Compliance with these regulations will place additional constraints on the design and operation of PW treatment plants and especially management and disposal of waste residuals from the treatment process. As with hazardous waste regulations, it is not clear if the radioactive waste exemption will apply if PW is reused outside of the O&G industry.

There has been considerable discussion of treating PW to a fit-for-purpose quality, not necessarily desalinating it to meet drinking water criteria. PW reuse options might include non-potable water supply, irrigation, discharge to a stream, or industrial uses such as process cooling water or supply for manufacturing facilities (NMED and ERG, 2024). New Mexico has standards that regulate the quality of surface water (20.6.4 NMAC) and groundwater (20.6.2 NMAC). Table 16 summarizes the standards for drinking water, irrigation water, livestock watering, chronic aquatic life, and groundwater with a TDS of less than 10,000 mg/L for constituents found at high concentrations in Permian Basin PW. There are approximately 90 constituents regulated under the federal SDWA. In addition, the regulations under the New Mexico Water Quality Act have standards for about 50 constituents in groundwater, and fewer regulated compounds for surface water used for irrigation, livestock water, or aquatic life; thus, Table 16 is only a partial list of regulated compounds. The regulations also contain narrative standards that address constituents that are toxic to humans or plant or animal life, or cause more than one cancer per 100,000 exposed persons. Comparing the standards summarized in Table 16 to the water quality summarized in Tables 19 and 20 (discussed below) shows that even if PW is not intended for potable use, it must be treated to a high quality for other surface water uses or where it might infiltrate to underlying aquifers due to its very high salinity. Although there are no enforceable standards for TDS for drinking water or surface water, unless a very large industrial demand can be identified for low quality water, high TDS water, reuse of PW will almost certainly require a high degree of desalination, likely greater than 99% TDS removal.

Table 16. Summary of selected water quality standards relevant to reuse of produced water for potable use, irrigation, livestock water, chronic aquatic life, and groundwater standards

	SDWA Standard	New Mexico Surface Water Standards 20.6.4 NMAC			20.6.2 NMAC
Constituent	**Drinking Water**	**Irrigation**	**Livestock Watering**	**Aquatic Life (Chronic)[1]**	**Ground-water**
Arsenic	0.01	0.1	0.2	0.15	0.01
Barium	2.0				2.0
Boron		0.75	5.0		0.75[2]
Chloride	250.[3]			230.	250.[4]
Ammonia (as N)				9.2[4]	
Selenium	0.05	0.25[6]	0.05		0.05
Sulfate	250.[3]				250.[4]
Uranium	0.03				0.03
Radium 226 + 228	5 pCi/L		30 pCi/L		5 pCi/L
Gross Alpha	15 pCi/L		15 pCi/L		
Benzene	0.005				0.005
Toluene	1.0				1.0
Ethylbenzene	0.7				0.7
Total Xylenes	0.01				0.62
Total Dissolved Solids	500.[3]				1,000.[3]

Notes:
[1]The chronic standard is a maximum concentration to protect aquatic organisms from long-term exposure to a contaminant
[2]Groundwater used for irrigation
[3]Secondary standard for drinking water
[4]Standard for domestic water supply
[5]Ammonia standard for water at pH 7.5, temperature = 20°C
[6]Selenium standard if sulfate concentration is greater than 500 mg/L

Produced Water (PW)

Produced water is the native water present in a subsurface formation that accompanies hydrocarbon fluids (i.e., oil and gas) as they are brought to the surface. In practice, it also includes water injected into the formation during fracking operations, known as flowback, and water or other fluids that may be injected into the formation to improve production by processes used in enhanced oil recovery (EOR), sometimes referred to as secondary oil recovery (SOR). Produced water generation will occur throughout the life of the well, whereas frack fluids return to the surface in a few weeks to a few months after fracking, and typically comprises 4-8% of the total volume of water generated during the life of a well (Kondash et al., 2017). The distinction between the quality of flowback and PW is diminishing as the industry increasingly turns to use of PW instead of fresh or brackish water for fracking (Figure 35). It is not feasible nor necessary to separate flowback from PW; therefore, the two fluids are managed together and commonly referred to simply as PW.

In discussing PW management, it is helpful to briefly review the recent production of O&G and PW in New Mexico. The principal O&G and CO_2-producing regions are shown in Figure 36 (Zemlick, 2017). The major O&G producing regions are the Permian Basin of southeastern New Mexico and the San Juan Basin of northwestern New Mexico. A comparatively small volume of natural gas is produced from coal beds in the Raton Basin in northern New Mexico, but this basin generates little PW compared to the rest of the state, less than 7 M bbls versus 2.3 B bbls in 2024 (NMOCD, 2025), and is not considered in this discussion.

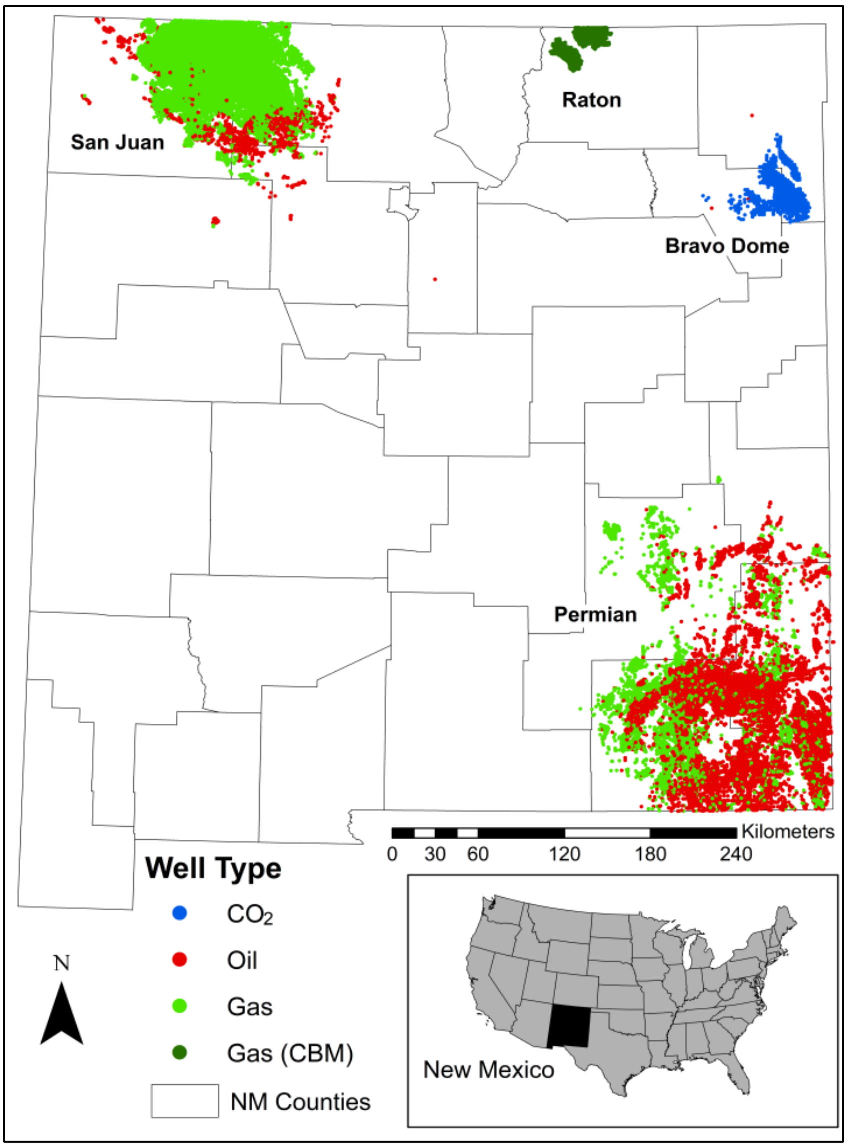

Figure 36. Oil, natural gas, coal bed methane, and CO_2 producing regions of New Mexico (Zemlick et al., 2017).

Volumes of Produced Water in New Mexico

Data on production of O&G, CO_2, and PW is compiled by the New Mexico Oil Conservation Division (NMOCD, 2025). Annual production of O&G from the Permian and San Juan Basins, along with total statewide production, is shown in Figure 37 (NMOCD, 2025). In 2024, the Permian Basin in New Mexico accounted for about 85% of the state's production of natural gas and greater than 98% of its oil production.

Generation of PW in the Permian and San Juan Basins from O&G production is shown in Figure 38 and tracks closely with O&G production shown in Figure 37 (NMOCD, 2025). As with O&G production, Permian Basin generates by far the greatest volume of PW, accounting for greater than 98% of the total volume produced in 2024.

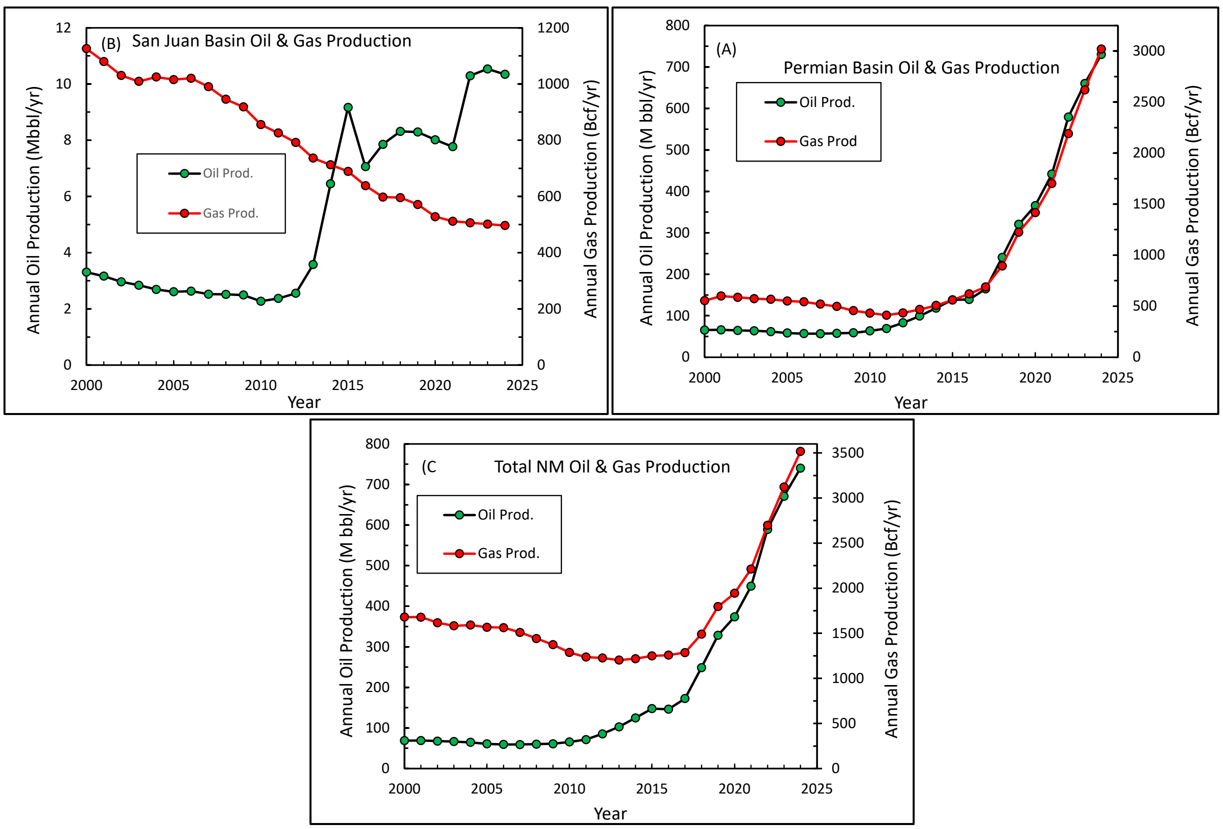

Figure 37. Summary of annual oil and gas production since 2000 in the (A) Permian Basin, (B) San Juan Basin, and (C) total statewide production (NMOCD, 2025).

The ratio of PW to oil production is shown in Figure 39 and can be seen to have approached a value of less than three. Scanlon et al. (2017) cite a ratio of 13 for conventional wells in the Permian Basin and a ratio of 3 for unconventional wells. Unconventional wells are completed in tighter formations, which release less formation water than conventional O&G wells. Thus, the decrease in the ratio from over 10 to less than 3 in the last 15 years reflects increased production from unconventional wells and decreased production from conventional wells.

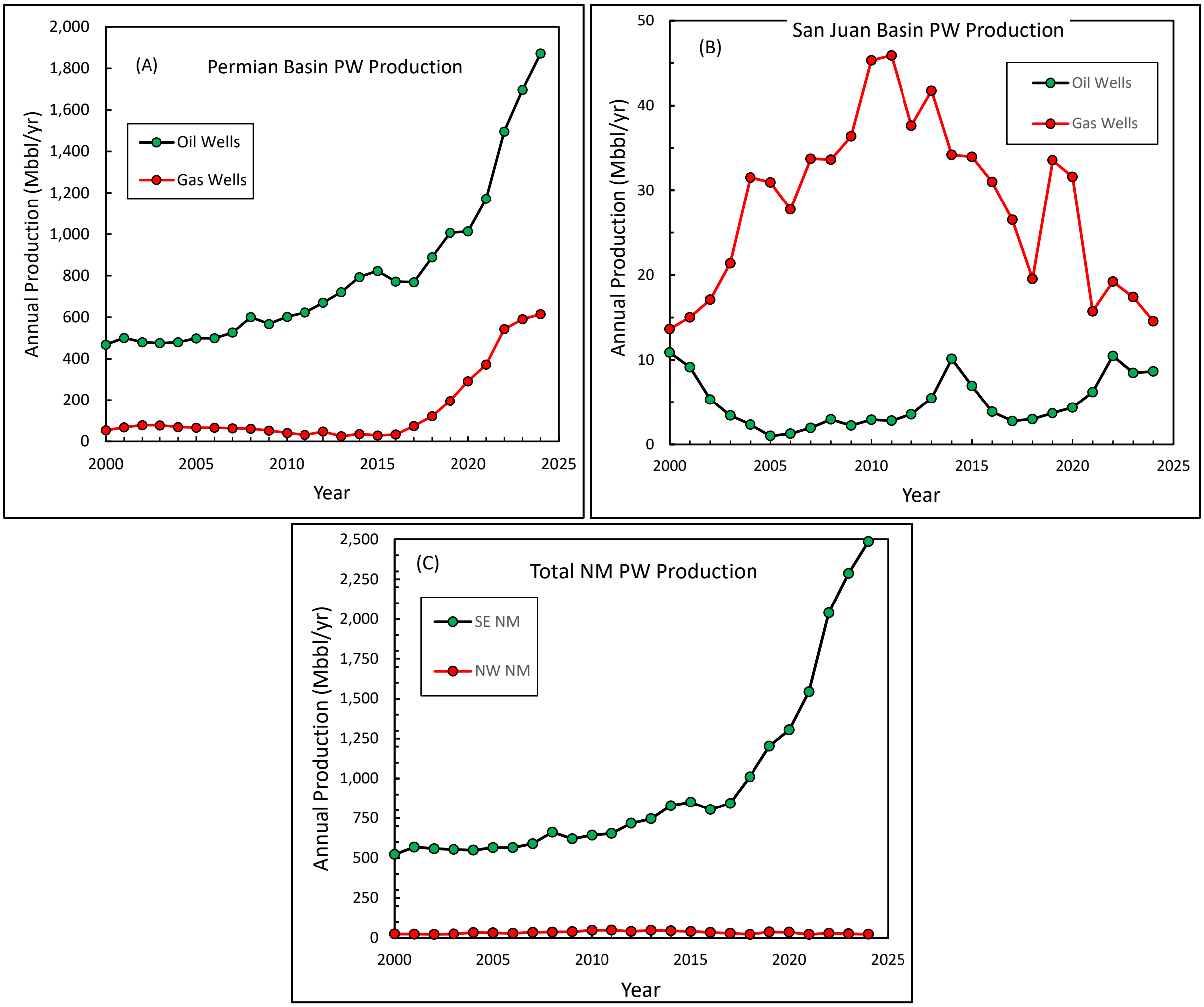

Figure 38. Summary of annual PW production since 2000 in the (A) Permian Basin, (B) San Juan Basin, and (C) total statewide production (units of million barrels per year) (NMOCD, 2025).

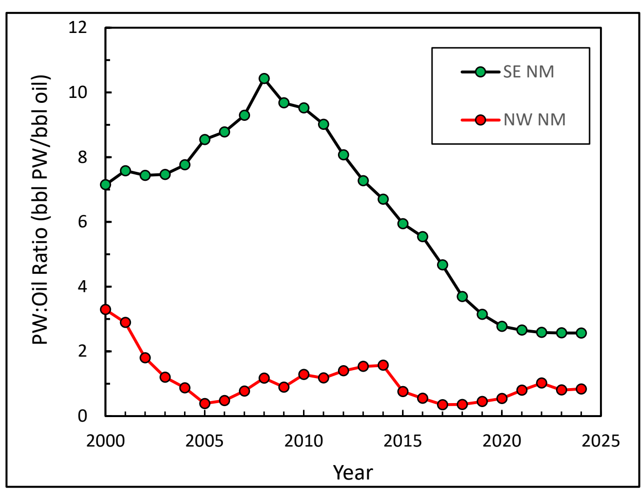

Figure 39. Ratio of the volume of PW to volume of oil produced (NMOCD, 2025).

Whereas the O&G industry reports liquid volumes in barrels (1barrel equals 42 gallons), water usage and resources are usually reported in units of acre-ft (1 AF = 326,000 gal = 1,233 m^3). To put the annual volumes of water used for fracking and PW generated by O&G production in perspective, it is useful to compare them to the volumes of fresh water used in the southeastern counties of New Mexico. Table 17 lists the 2024 volumes of fresh and brackish/saline/produced water used for fracking, and the volume of PW generated (Valdez et al., 2024). The volume of fresh water used for irrigated agriculture and livestock watering as well as the total volume of fresh water used for all purposes in the four southeastern counties, which overlie the Permian Basin, is provided for comparison (Valdez et al., 2024). Except for 100,000 AF/yr of water supplied by the Pecos River for irrigated agriculture and livestock watering in Chavez and Eddy Counties, virtually all of the water used in the four counties of the southeastern corner of New Mexico is supplied by groundwater. This emphasizes the importance of protecting this resource.

Table 17. Comparison of annual water volumes used for fracking, PW generated by O&G production, and fresh water use in Chavez, Eddy, Lea, and Roosevelt Counties

Description	**Annual Water Volume (AF)**
Water for Fracking in 2024[1]	47,100
Fresh Water	1,330
Brackish, Saline and PW	45,800
PW generated in 2024[1]	324,000
Water Use in Southeastern NM Counties in 2020[2]	
Irrigated agriculture and livestock	782,000
Public and domestic supply	49,900
Commercial and industrial supply	9,600
Mining and power	66,400
Reservoir evaporation	21,100
Total water use	928,600

Notes:
[1]Data source: NMOCD, 2025
[2]Data sources: Valdez et al., 2024

Current Management of Produced Water

Currently, treatment and use of PW outside of the O&G industry is not allowed in New Mexico (20.6.8 NMAC). Therefore, all PW must either be disposed of by injecting it into salt water disposal (SWD) wells or reused within the industry. Reuse within the industry consists of using it for fracking or subsurface injection to support enhanced oil recovery (EOR). Since virtually all water used for fracking comes back to the surface as flowback mixed with formation water, this really does not constitute a disposal method. There are a few mid-stream companies offering produced water disposal through use of evaporation ponds, but the volume of water disposed in this manner is not reported to the NMOCD. Salt water disposal wells are regulated as Class II underground injection control (UIC) wells under the Resource Conservation and Recovery Act (RCRA) which is administered by the NMOCD.

The statewide annual volume of PW disposed in SWD wells and re-injected for EOR is summarized in Figure 40. This figure shows that the fraction of water disposed in SWD wells has been increasing in recent years primarily because unconventional O&G formations have such low permeability that water injection for EOR has limited effectiveness. At the end of 2024, New Mexico had 817 completed SWD wells and 3096 injection wells (NMOCD, 2025).

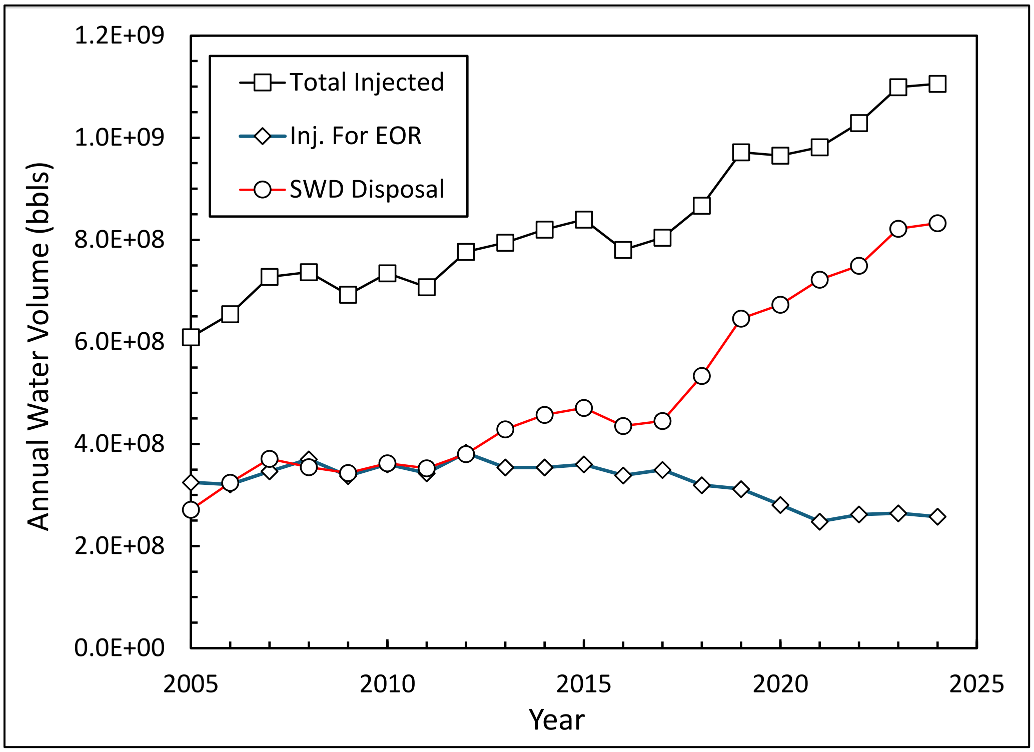

Figure 40. Statewide annual volume of produced water (PW) generated, that was disposed of in salt water disposal (SWD) wells, and that was injected for enhanced oil recovery (EOR) (NMOCD, 2025).

Lemons et al. (2019) summarized the geologic, geographic, and temporal trends on PW disposal in the Permian Basin. A number of mid-stream companies manage PW for the O&G industry through collection, transportation, recycle, disposal, and reuse, which principally consists of PW used for fracking. To facilitate their operations, some of these companies have constructed large diameter (greater than 12 in) pipelines that gather and transport water to disposal, recycling, and reuse facilities. A description of some of these pipeline companies is published in O&G trade magazines such as the "American Oil and Gas Reporter" (Boyd, 2023). However, a compilation of the pipelines, their capacity, and the source and destination of the water they transmit is not available. The NMOCD lists over 200 pipeline companies and nearly 800 licensed water haulers operating in New Mexico (NMOCD, 2025). Certainly, the vast majority of water transported by these companies is within the state, primarily from wellheads and tank batteries to recycling and disposal facilities. Information on the volumes, sources, and destinations of their cargo is not available. However, based on the difference between the volume of PW generated (Figure 38) and the volume disposed or injected for EOR (Figure 40), it appears likely that a large volume of PW generated in New Mexico is sent to Texas, where regulations on disposal are less stringent.

Collecting, transporting, and deep well disposal of PW is expensive. These costs are difficult to obtain because companies consider this information proprietary; however, trade magazines and conversations with industry representatives cite transportation and disposal costs in the range of \$0.50 to \$1.50 per bbl of PW (Michael et al., 2019; Wiseman, 2020). The Texas Produced Water Consortium reports that disposal costs in Texas range from \$0.60 to \$0.70/bbl. The cost of disposal is important because it is one of the factors that determines whether PW is disposed of or treated for reuse; treatment and reuse becomes economically justified when these costs are cheaper than disposal. The industry recognizes that the ability to dispose of PW is critical to continued O&G development in the Permian Basin (Michael et al., 2019, Scanlon et al., 2020a, 2020b).

The biggest constraint on deep well disposal of PW is induced seismicity, the increased proliferation of earthquakes as a result of high-pressure injection of large volumes of fluid into deep formations. A large number of scientific investigations have been conducted on induced seismicity to understand the consequences of injection of fluids for energy storage (i.e., hydrogen), carbon sequestration (CO_2), hydraulic fracturing, and PW disposal. A summary of the geophysics of induced seismicity has been provided by Elsworth et al. (2016) and Schultz et al. (2020). Recent work correlating earthquake activity in the Permian Basin to subsurface injection of fluids for fracking and PW disposal has been published by Moein et al. (2023), Schultz et al. (2020), Skoumal et al. (2020), Skoumal and Trugman (2021), Smye et al. (2024) and Snee and Zoback (2018).

Figure 41 presents the location of earthquakes between 2000 and 2017 in the Permian Basin (Skoumal and Trugman, 2021). Figure 42 shows annual O&G production, PW disposal, and the number of earthquakes on the Texas side of the Permian Basin. Whereas in other O&G basins in the country a sizable fraction of induced seismic events is attributable to fracking, Skoumal and Trugman (2021) conclude that approximately 95% of the earthquakes in the Permian Basin are the result of PW disposal in SWD wells. In recent years, there have been an increasing frequency of earthquakes of magnitude 3 or greater occurring in southeastern New Mexico including a magnitude 4.49 earthquake near Carlsbad, New Mexico in February 2024 and a magnitude 5.4 earthquake in west Texas, 35 miles south of White City, New Mexico in February 2025 (USGS, 2025). For reference, earthquakes of magnitude 5 are sufficiently powerful to cause minor damage to buildings and their contents.

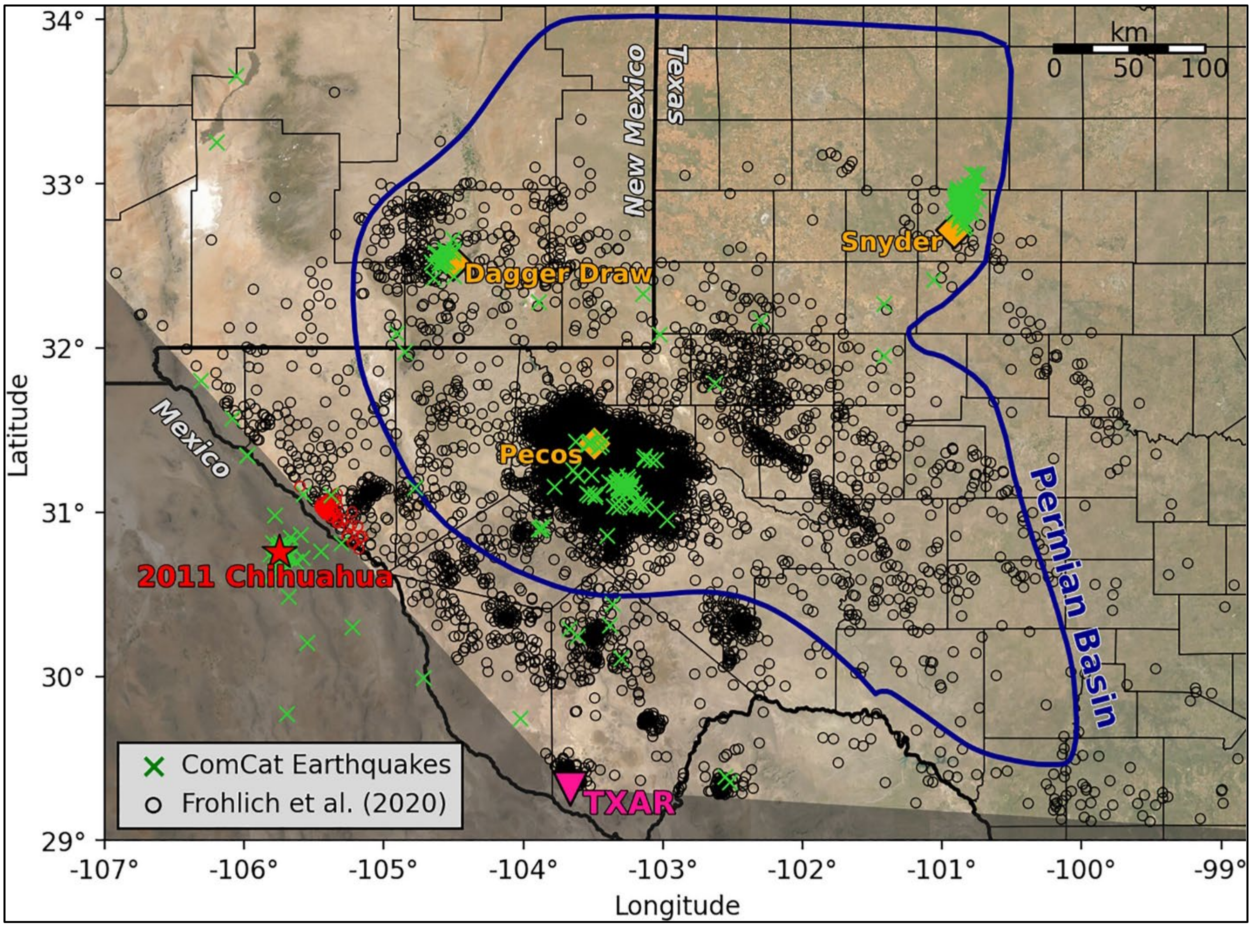

Figure 41. Map of seismicity near the Permian Basin. Circles represent earthquakes from Frohlich et al. (2020) and (×s) represent earthquakes in the Advanced National Seismic System Comprehensive Earthquake Catalog during 2000–2017 (Skoulman and Trugman, 2021).

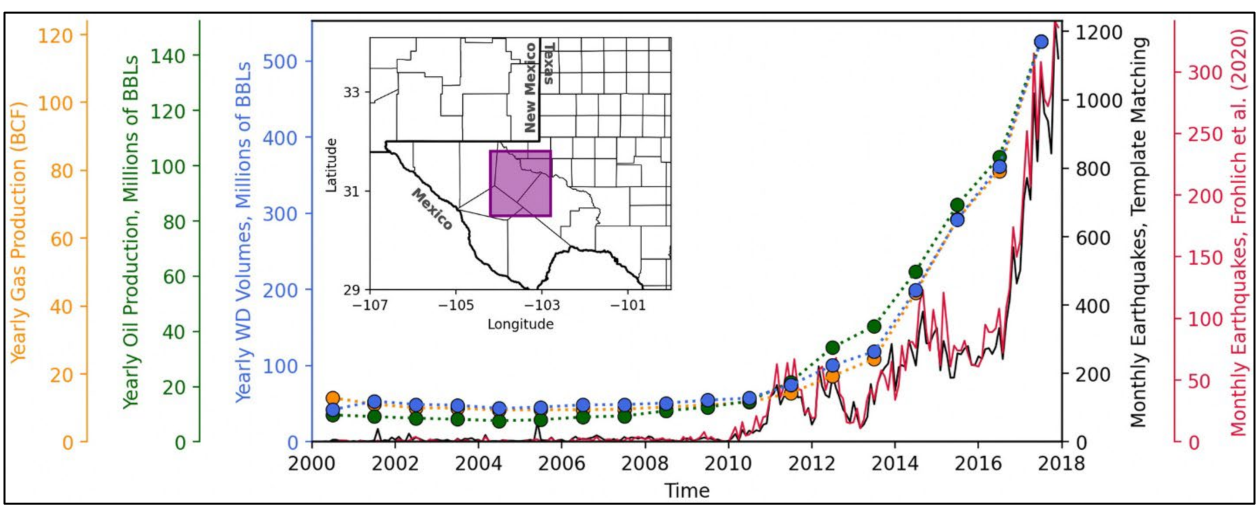

Figure 42. Comparison of wastewater disposal (blue), oil production (green), and gas production (yellow) volumes with earthquakes from Frohlich et al. (2020) (red) in the region around Pecos (purple rectangle, inset) (Skoumal and Trugman, 2021).

The NMOCD lists 1817 SWD wells and 3,096 injection wells in operation in 2024 (NMOCD, 2025). Concern about induced seismicity has led to consideration of imposing tighter constraints on operation and location of SWD wells by the NMOCD. The current permitted maximum injection pressure is 0.2 psi/ft multiplied by the depth of the top perforation or top of the open-hole completion. Thus, the maximum injection pressure at the surface for a well where the perforated casing begins at a depth of 7,000 ft would be 1,400 psi. An alternative approach would allow an operator to inject fluid at a pressure up to 50 psi less than the break-over pressure (the pressure that causes fractures in the subsurface formation) (GWPC, 2020). Current allowable spacing between SWD wells ranges from 0.5 miles to 1.5 miles depending on the volume of water to be disposed of. Scanlon et al. (2019) discuss fluid management strategies to reduce the risk of induced seismicity in several different basins. The GWPC (GWPC, 2020) has provided a comprehensive discussion of PW management strategies to reduce earthquake risks.

The rapid growth in the volume of PW requiring disposal (Figure 40), coupled with the high costs and possible limitations on disposal capacity, has led to concerns that the inability to dispose of PW may limit future O&G development in New Mexico (Michael et al., 2019; Scanlon et al., 2020a; Xu et al., 2013). This provides a strong incentive for the industry to identify alternative methods of managing PW, especially treatment and reuse as described in the state's Strategic Water Action Plan (NMED and ERG, 2024). The technical, economic, and regulatory challenges of PW treatment and reuse are substantial.

Chemistry of Produced Water

Produced water must be treated before it can be reused or disposed. The type of treatment depends on both the quality of the water and its planned use. If it is being used within the O&G industry for EOR, fracking, or deep well disposal, treatment may simply consist of processes to prevent plugging of the deep formation. Treatment methods typically utilize filtration to remove suspended solids and oily residue and may include addition of scale inhibitors and biocides to prevent microbial growth, which will clog underground formations and may contribute to microbially induced corrosion. If the water is to be used for public or industrial supply, irrigation, or discharge to a surface water, it must be treated to a much higher quality. Produced water in New Mexico has high salinity and therefore its use for these purposes will require desalination.

The chemical quality of PW varies widely throughout the country and it also varies widely within each O&G producing region (Kondash et al., 2017). Furthermore, its high salinity complicates chemical analyses, especially for trace constituents (Jiang et al., 2021). The USGS (Blondes et al., 2024) maintains a large database on PW that lists the geochemistry and other information on nearly 115,000 PW samples from locations throughout the country. Depending on the analytes for each sample, data may include information on sample location, major ion chemistry, trace elements, isotopes, and time-series data. The very large amount of data prevents generalization of PW quality from O&G development. Furthermore, much of the data is from older, conventional wells. The characteristics of PW from unconventional shale and tight sand formations is often quite different.

The review paper by Danforth et al. (2020) summarized the results of 129 studies that included data on major and minor constituents in 173 sources of PW from wells in Canada, Mexico, and the continental U.S. Only two papers containing information on PW quality in New Mexico were cited in this review. A notable finding in this review was that of 1,198 unique chemicals that had been detected in PW, only 246 compounds had been detected more than once.

There are several reviews of PW characteristics in the western and southwestern U.S. Benko and Drewes (2008) published a survey of the quality of PW from O&G production and coal bed methane (CBM) production in the western U.S., while Scanlon et al. (2020c) provided more recent data for PW from production wells closer to New Mexico. The results for salinity are presented in Figure 43 (Scanlon et al., 2020b, 2020c), which shows a wide range of concentrations, typically at least two orders of magnitude, for nearly every basin. Of particular relevance to New Mexico, is that the average TDS of PW from unconventional O&G wells in the Permian Basin is over 100,000 mg/L (100 g/L), compared to less than 20,000 mg/L (20 g/L) in the San Juan Basin. Not shown in the figure is the TDS of PW from coal bed methane production in the Raton Basin, which is reported in the paper to have a mean TDS concentration of 1,500 mg/L (Benko and Drewes 2008). This paper also includes information on the occurrence and concentrations of about 20 hydrocarbons associated with O&G including benzene, toluene, ethylbenzene, and xylenes (BTEX).

The water quality characteristics of the San Juan and Permian Basins are briefly summarized below. A discussion of the PW quality in the Raton Basin has been provided by Wolfe et al. (2015) and Dahm et al. (2011), but it is not discussed in this paper due to the relatively small volume of PW generated from this basin in New Mexico.

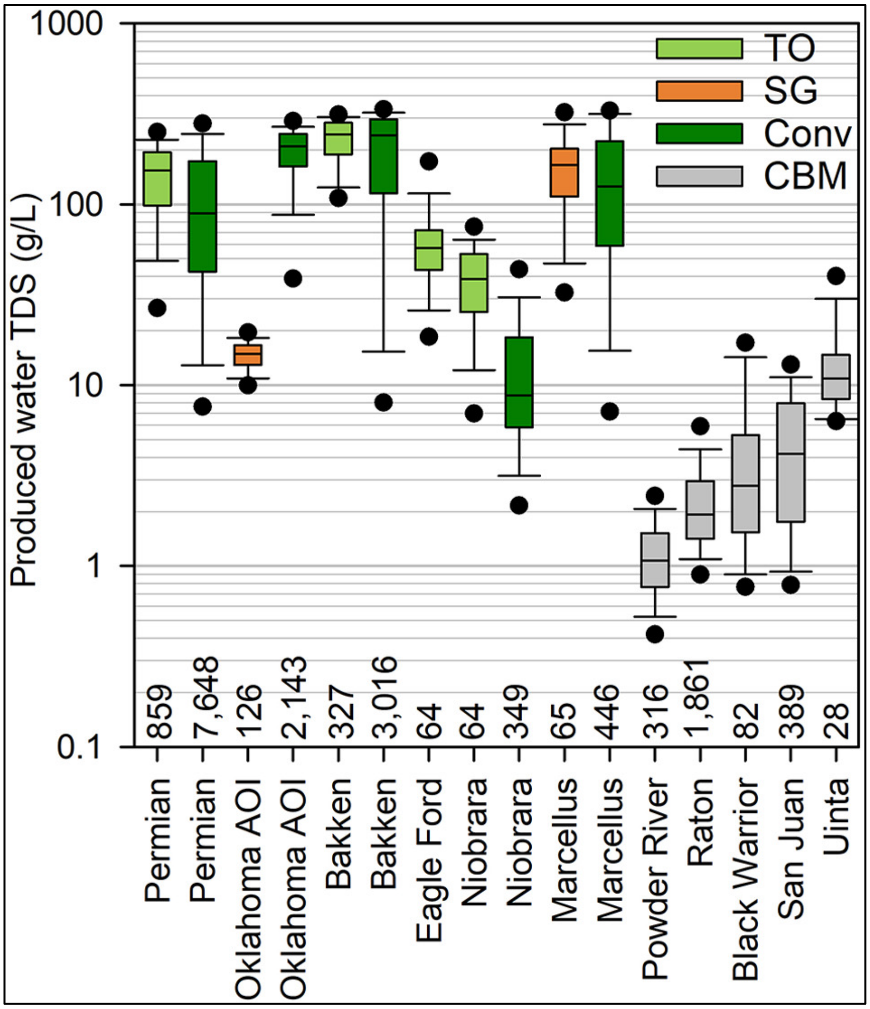

Figure 43. Total dissolved solids concentrations for produced water quality near New Mexico. TO = tight oil, SG = shale gas, Conv = conventional oil and gas, CBM = coal bed methane. The numbers on x-axis refer to the number of analyses (Scanlon et al., 2020b).

San Juan Basin

Largely because the volume of PW generated in the San Juan Basin represents less than 3% of the total PW generated in New Mexico (see Figure 38), this water has received less attention to its characteristics and management. Simpson (2006) summarized the results of pH and TDS analyses of 1,253 PW samples from four different strata in the basin. From shallowest to deepest, the formations were the Fruitland Formation, the Pictured Cliffs sandstone, the Mesaverde Formation, and the Dakota sandstone. A summary of the results of these analyses is presented in Table 18. This report does not list the concentrations of other constituents in the PW.

Table 18. Summary of pH and TDS measurements for produced water samples from oil and gas wells in the San Juan Basin (Simpson, 2006)

	pH			**TDS (mg/L)**		
Formation	**Minimum**	**Maximum**	**Mean**	**Minimum**	**Maximum**	**Mean**
Fruitland	5.47	9.14	7.62	5,421	32,628	16,093
Pictured Cliffs	7.37	10.27	8.14	609	64,980	21,420
Mesaverde	6.73	9.92	7.7	1,077	71,856	18,906
Dakota	6.71	8.28	7.5	4,399	102,834	25,090

Dahm et al. (2011) and Scanlon et al. (2020b, 2020c) provide more complete information on the PW quality from CBM wells in the San Juan Basin including a searchable list of all data, but they did not distinguish between PW from the individual formations (Table 19). The Fruitland Formation is the principal source of coal bed methane in this basin. This data is from more than 550 samples. The concentrations of trace elements were also reported but from only 19 or fewer samples. The large standard deviations for many of the parameters is an indication of outliers in the dataset with very large concentrations. The low sulfate concentration in PW from coal bed methane wells is due in part to microbial activity where methanogenic sulfate-reducing organisms reduce sulfate to sulfide (H_2S).

Table 19. Summary of produced water chemistry from coal bed methane wells in the San Juan Basin. All units are in mg/L except pH (Dahm et al., 2011)

			Percentile		
Parameter	**Average**	**Std. Dev.**	**25%**	**50%**	**75%**
pH	7.82	0.52	7.5	7.84	8.18
TDS	4,693	4,209	1,766	3,097	6,957
Alkalinity[1]	3,181	2,207	1,648	2,421	4,905
Calcium	53.29	276.29	9.20	24.00	40.00
Chloride	624.	1,649	29	89.	545
Magnesium	15.45	30.68	2.70	8.00	16.00
Potassium	26.99	89.72	4.75	8.60	16.00
Sulfate	25.73	122.63	BDL[2]	BDL[2]	6.75

Notes:
[1]Alkalinity in units of mg $CaCO_3$/L
[2]Below detection limit

Permian Basin

There is considerably more information on the quality of PW from the Permian Basin than from the San Juan Basin. Whereas many of the older reports simply summarized the salinity of these waters, research reports in the last decade have contained analyses of the major ion chemistry, trace element chemistry, and in a few cases, analyses of organic constituents and radionuclides.

Recent studies of Permian Basin PW quality include reports by Chaudhary et al. (2019), Engle et al. (2016), Jiang et al. (2022c), Khan et al. (2016), Scanlon et al. (2017, 2020a, 2020b), and Thacker et al. (2015). The most comprehensive reporting of Permian Basin PW quality was published by Jiang et al. (2022a, 2022b), which analyzed samples from 46 Permian Basin O&G wells primarily in New Mexico. The analytes consisted of an extensive suite of inorganic compounds as well as organic constituents. One PW sample was analyzed for per- and polyfluoroalkyl substances (PFAS) compounds and 10 samples were analyzed for radionuclides. Results for selected constituents are summarized in Table 2. The compounds listed in this table are constituents that will challenge desalination technologies, or are hazardous or radioactive and may affect waste management options. The original paper has a complete list of all the analytes detected (Jiang et al., 2022c).

Jiang et al. (2022b, 2022c) reported detection of a large number of compounds that were described as non-targeted constituents. These are compounds that appear as unknown peaks in a scan from an analytical method such as gas or liquid chromatography or mass spectroscopy, but the specific compound cannot be identified by the analyses. Typically, these were hydrocarbons associated with oil that appear as unknown peaks in chromatographic scans. An earlier study by Khan et al. (2016) used an advanced gas chromatography-time-of-flight-mass spectrometry (GC-ToF-MS) technique to characterize volatile organic compounds (VOC) in PW from eight wells in the Permian Basin in Texas. Approximately 1400 organic chemicals were detected (i.e., peaks were discernible on a chromatogram), but only about 330 of them had identifiable structures. Although many hydrocarbons were identifiable, only six hydrocarbons are regulated by the federal SDWA (BTEX compounds: benzene, toluene, ethyl benzene, and three isomers of xylene). Butkovskyi et al. (2017) presented the results of a literature search on organic compounds identified in PW and found that that those with potentially harmful effects consisted of compounds from the formation (i.e., polycylic aromatic hydrocarbons and phthalates), fracking fluids (biocides and 2-butoxyethanol), and possibly downhole transformations of organic compounds (carbon disulfide, and halogenated organic compounds, although few were reported). Most of the hydrocarbons from oil-contaminated water exhibit little or no toxicity.

Analyses of PW from 46 Permian Basin O&G wells by Jiang et al. (2022b, 2022c) confirm that it is an extremely high salinity water with a mean TDS concentration of 128,641 mg/L. A study by Ghurye et al. (2021) of commingled PW from multiple wells sent to an industrial recycling facility found an even higher average TDS of 245,691 mg/L. The chemistry of Permian Basin PW is dominated by very high concentrations of sodium, calcium, and chloride. High concentrations of hazardous constituents (arsenic and selenium), radionuclides (thorium, uranium, and radium), and regulated organic compounds (BTEX compounds) are also frequently present. Ninety-one analytes were detected out of 309 targeted compounds. Twenty-eight organic compounds were quantitatively identified while 218 other constituents were not detected. The analytical method used for PFAS targeted 34 compounds out of thousands of possible chemical species. Only five of these compounds were detected, and all were at or below the reporting limit; none of the other per-fluorinated species were detected.

A frequent public criticism of PW is that there is inadequate knowledge of the contaminants in it, and the difficulties these constituents present when treating or disposing of the water. Therefore, perhaps the most important finding of the results by Jiang et al. (2022b, 2022c) was that despite doing an exhaustive characterization of a large number of PW samples, there were no unexpected findings of constituents with unusual toxic or hazardous characteristics, nor constituents that are difficult to remove by conventional treatment processes.

There has been some interest in recovering critical minerals from PW such as cobalt, lithium, magnesium, manganese, and rare earth elements (also referred to as lanthanides). Smith et al. (2024) summarized annual production of these constituents from 12 different O&G producing basins and estimated that Permian Basin PW produced 770,000 tonnes/yr of lithium, 82,000,000 tonnes/yr of magnesium, and 230,000 tonnnes/yr of manganese, by far the biggest critical minerals production from any O&G basin in the U.S. They did not report production of rare earth elements.

While the masses of these critical minerals are large, the concentrations of these constituents in the PW are low (see Table 20); the large annual production is due to the very large volumes of PW generated in the Permian Basin. Miranda et al. (2022) estimated that an oil well producing 72,000 bbl/yr (12,000 m^3/yr) would generate \$16,000/yr from recovery of lithium, \$44,500/yr from recovery of magnesium, and \$190,000/yr from recovery of strontium. This is based on assuming an optimistic 95% recovery of each element. For example, reviews of lithium recovery by Khalil et al. (2022) and Warren (2021) report recovery efficiencies for conventional processes ranging from 40% to 93%. Furthermore, the techno-economic assessment by Warren (2021) suggests that lithium recovery from brines may not be economically justified at concentrations below 100 mg/L. The data in Table 20 show average lithium concentrations in Permian Basin PW of 22 mg/L. Assuming a desalination plant recovers 75% of the feed water, the lithium concentration in the concentrate would be around 80 mg/L, thus it is not clear that lithium recovery would be economically viable from this water. Nevertheless, mineral recovery from PW should continue to be investigated because, if feasible, it would offset the high cost of PW treatment and possibly reduce the volume of waste requiring disposal.

Table 20. Summary of produced water chemistry for selected constituents from 46 wells in the Permian Basin. All units are mg/L except as noted (Jiang et al., 2022b, 2022c)

				Percentile		
Parameter	**Mean**	**Max**	**Min**	**25%**	**50%**	**75%**
Inorganic Compounds						
pH[1]	6.6	8.1	3.9	6.3	6.7	7.0
TDS	128,641	201,474	100,830	113,441	122,280	134,525
Alkalinity[2]	272	870	100	128	207	336
TOC[3]	103.5	248.1	2.4	28.	90.6	173.3
Ammonia	432	750	320	330	400	495
Arsenic	3.17	6.04	1.62	1.74	2.64	4.61
Boron	42.34	76.50	17.20	33.29	40.65	51.03
Calcium	3,821	8,186	880	1,705	3,531	5,744
Chloride	76,648	120,200	57,543	69,269	75,658	86,979
Lithium	22.39	52.28	11.74	20.00	21.02	23.40
Magnesium	745.0	1,877.	259.3	472.7	621.3	959.1
Manganese	.488	1.239	.010	.116	.427	.781
Potassium	923	3,637	222	449	808	1,171
Selenium	2.5	2.5	2.5	-	2.5	-
Silica	107.7	195.4	4.0	29.2	115.7	178.2
Sodium	40,896	68,985	25,080	37,000	39,673	42,967
Strontium	450.	1404.	28.9	116.4	325.	817.
Sulfate	496	965	151	243	510	690
Radionuclides[4]						
Gross Alpha	1,105.6	1,630	660	745	863	1,630
Radium-226 + 228	469.3	1,546	3.3	156.6	345.8	700.5
Organic Compounds						
Benzene	2.611	4.900	1.900	2.20	2.20	2.60
Ethylbenzene	.112	.160	.072	.093	.110	.130
Toluene	2.53	3.70	1.70	2.00	2.40	2.90
Xylenes (Total)	1.19	1.60	.71	1.10	1.30	1.40
Total Petr. H-carbons[5]	.447	.89	.34	.39	.53	.61

Notes:
[1]pH units
[2]Alkalinity in units of mg $CaCO_3$/L
[3]TOC is Total Organic Carbon
[4]Radionuclides are in units of pCi/L
[5]Total petroleum hydrocarbons reported as n-Decane

Treatment of Produced Water

A brief review of brackish water desalination technologies was presented in this paper's section on Brackish Groundwater Resources. Due to the comparatively low salinity of PW from the San Juan Basin, conventional desalination processes such as RO that are appropriate for brackish groundwater desalination may be technically feasible. The principal challenges to treating this water are: (1) mineral scale formation at high feed water recovery, (2) corrosivity of high salinity waters, (3) high energy costs, and (4) the challenges of concentrate management and disposal.

There is a growing body of literature on desalination of very high salinity PW, such as that found in the Permian Basin. However, these studies are primarily limited to generic discussions of the technologies and challenges, and descriptions of laboratory studies (Al-Ghouti et al., 2019; Amakiri et al., 2022; Igunnu and Chen, 2014; GWPC, 2019; Sullivan Graham, 2017; Salinas-Rodriguez and Schippers, 2021, Cooper et al., 2021; EPA, 2018; Youssef et al., 2014). The wide variation in chemistry and salinity of PW throughout the country means that technologies that work in one basin may not be appropriate for O&G basins in New Mexico. Therefore, the review presented here is limited to studies and technologies that are relevant to treatment of Permian Basin PW.

The extremely high salinity of Permian Basin PW, typically three times the salinity of seawater, precludes use of RO because the very high osmotic pressure means transmembrane pressures are greater than membranes can withstand and greater than what high pressure pumps can provide. Some manufacturers offer high pressure RO membranes; however, no reports of application of this technology to Permian Basin PW have been found. Similarly, electrodialysis reversal (EDR) is not practical for very high salinity solutions due to diminished current efficiencies, transmembrane water transport, and membrane resistance (Shah et al., 2022). Forward osmosis (FO) is a process that uses salinity gradients to desalinate water instead of pressure gradients and was studied for PW desalination several years ago, but has not received much attention in recent years (Coday et al., 2014; Bell et al., 2017). Hybrid treatment trains and novel technologies have been proposed, but are not ready for field-scale application and are therefore not discussed here unless they have demonstrated in laboratory experiments. A summary of the general classes of desalination processes and the range of salinities for which they are commonly applied is presented in Figure 44.

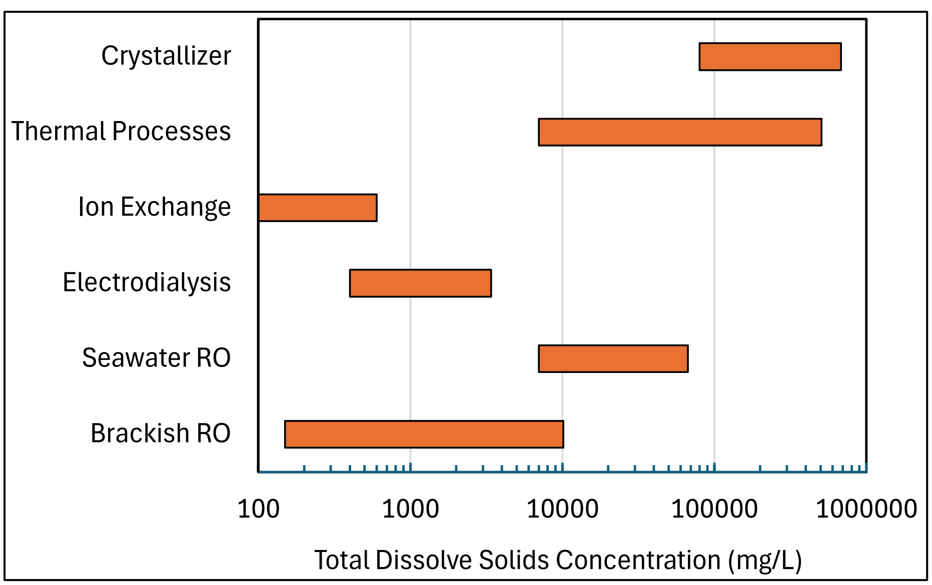

Figure 44. Salinity range for different desalination processes (adapted from Salinas-Rodriguez and Schippers, 2021 and Shah et al., 2022).

Scanlon et al. (2020b) published one of the first critical reviews of the potential for beneficial reuse of PW outside of the energy industry and identified the following limitations for reuse of Permian Basin PW: (1) poor knowledge of PW chemistry, (2) inability to accurately measure PW quality due to a high salinity matrix and interference issues, (3) lack of acceptable measurement techniques, (4) absence of suitable standards, and (5) lack of regulations for various sectors in light of the complexity of PW. However, as described in the review in this report, remarkable progress has been made to address the first three limitations; robust methods have been developed for analyzing very high salinity PW and have generated a well-documented quantitative understanding of the chemistry of Permian Basin PW. Scanlon et al. (2020b) also note that suitable technologies for treating PW were not well developed at that time. They concluded that "water scarcity issues are more readily addressed by reusing PW within the energy sector rather than by the beneficial use of PW outside of the energy sector." Recent developments of PW treatment technologies described below provide information to evaluate whether this conclusion is still valid.

Although there have been many decades of research on desalination, there is a limited body of published work on desalination of very high salinity water. Khlaifat et al. (2024) provided diagrams and a brief description of 14 desalination methods. However, no quantitative information was given on their cost or performance. Furthermore, there was no discussion of the challenges each method would face when treating very high salinity PW such as occurs in the Permian Basin. Similarly, Eyitayo et al. (2023a, 2023b) provided a general summary of treatment technologies of PW for fit-for-purpose uses within the O&G industry and described how emerging technologies can be integrated to achieve different treatment goals depending on the final use of the treated water.

Shah et al. (2022) published an extensive literature review of the theory and practical aspects of ten existing and emerging technologies for high salinity desalination. Several challenges that were common to these technologies were noted:

- Mineral scale formation on membrane and heat transfer surfaces that limited flow through membranes and heat transfer across heat exchangers
- Corrosion potential from high chloride waters that requires use of expensive corrosion resistant materials such as super-duplex stainless steel and titanium
- Thermodynamic inefficiencies of thermal processes resulting in high energy requirements
- Very high osmotic pressures that exceed those which can be used for membrane processes

Ghurye et al. (2021) reviewed desalination methods for very high salinity PW in the range of 200,000 to 250,000 mg/L and noted that its high salinity and complicated chemical matrix make desalination extremely difficult. The study concluded that crystallization or total evaporation are the only technologies able to treat such high TDS waters at scale. A theoretical model was developed and compared to the results of a bench-top crystallizer, which found good distillate quality, although with significant carryover of light organics such as BTEX compounds and ammonia. Sequential formation first of low solubility sulfate salts was followed by NaCl precipitation, and finally precipitation of high soluble chloride salts of Mg, K, and Ca. This suggests possible recovery of NaCl as a commodity. Generation of very large volumes of salt in the waste concentrate was identified as a major drawback of full desalination of PW by evaporation.

Thermal desalination processes are more energy intensive than membrane processes primarily due to the high latent heat of evaporation of water. The energy requirements for thermal desalination can be moderated somewhat by secondary heat recovery. However, energy recovery using heat exchangers for low temperature differentials is expensive and inefficient (Shah et al., 2022; Lienhard et al., 2017). The advantage of thermal processes is that, at present, they are the only technologies that can desalinate very high salinity PW, although development of ultra-high pressure RO technology is an area of current research.

One frequently expressed concern about Permian Basin PW treatment processes is that, while there are numerous studies of theoretical or laboratory bench-scale treatment methods, there are no reports of long duration field-scale pilot plants in the scientific or engineering literature. There are numerous examples of company reports of successful desalination of Permian Basin PW; however, virtually none of these reports include sufficient technical information that could be used to validate their claims. A few examples of companies claiming mature PW desalination technologies include Bechtel (2025), Tetra Technologies Inc. (2025), Genesis Water Technologies (2020), and Hart Energy (2022).

The New Mexico Produced Water Consortium (NMPWRC, 2025) is collaborating with industrial partners in a number of field-scale pilot desalination projects. These projects are summarized in Table 21. Most are in progress so information on them is not complete. However, one of the requirements of participating with the Consortium is submittal of a final report that will be published on their website.

One of the New Mexico Produced Water Consortium projects that has provided more complete information is that done by Crystal Clearwater Resources (CCR, 2023). The project's plant consisted of a low temperature thermal distillation process. The results of a 19-day operating run of the process found that it was able to produce over 200 bbl/d (36 m^3/d) of distillate with an average TDS of less than 400 mg/L. The distillate had concentrations of BTEX compounds exceeding SDWA standards, therefore it was subjected to post treatment organics removal by GAC. This reduced the concentrations of BTEX and other volatile organic compounds to below detection limits. The system operated between 9 and 16 hours each day, with only three short interruptions due to equipment problems.

In its annual report, the Texas Produced Water Consortium (TPWC) listed five pilot projects treating Permian Basin PW that have operated at a scale of 100 bbl/d or greater for periods of at least three months. Brief summaries of the projects are contained in the Consortium's annual report; however, few details other than those summarized in Table 22 were provided (TPWC, 2024).

Table 21. Field-scale pilot produced water treatment projects done in collaboration with the New Mexico Produced Water Research Consortium (NMPWRC, 2025)

Technology	Flow Rate (bbl/d)	Duration (months)	Inlet TDS Range (mg/L)	Finished Water TDS (mg/L)	Recovery (%)	Company
Multistage flash distillation	200	2	120,000 – 150,000	<400	50	Crystal Clearwater Resources
Multistage flash distillation	100	2	100,000	500	50	Devon/Crystal Clearwater Resources
Multistage vapor recompression	150	NR	120,000	200	50	Circle Verde
High pressure vaporization	500-800	7	100,000	<100	NR	Bechtel
Freeze separation and RO polishing	20	7	100,000	200	NR	Texas Pacific Water
High pressure RO	500	8	100,000	1,000	NR	NGL
Membrane and thermal processes	20	4	100,000	500	NR	Joint Industry Program

Table 22. Summary of large-scale pilot projects treating Permian Basin produced water (TPWC, 2024)

Technology	Flow Rate (bbl/d)	Duration	Inlet TDS Range (mg/L)	Finished Water TDS (mg/L)
Thermal desalination	>100	4 months	111,000 – 140,000	311
Thermo-mechanical desalination	350	7 months	125,000 – 190,000	36
Adv. Membrane desalination	500	4 months	120,000	900
Adv. Thermal desalination	>100	NR[1]	120,000	456
Reverse Osmosis	132	NR[1]	55,000	179

[1]Not reported

Tarazona et al. (2024a) evaluated the treated water chemistry and its toxicology of a thermal distillation process in which low grade heat from a diesel engine was used to treat 100 m^3/d of PW. The system achieved 38% feed water recovery; however, details on the distillation process including duration of the testing was not provided. The distillate had a TDS of 475 mg/L and was analyzed for a suite of inorganic and organic compounds. However, basal toxicity tests of the distillate found that it was toxic for a number of test chemicals, primarily due to high concentrations of volatile and semi-volatile organic compounds, as well as ammonia (NH_3), cadmium (Cd), and copper (Cu). The distillate was then subjected to further treatment in a laboratory setting by adsorption in a GAC column, followed by ammonia removal in a zeolite column. The two post treatment processes each individually reduced the treated water's toxicity, and when combined, reduced the toxicity so that it met NPDES whole effluent toxicity criteria.

Desalination is an energy intensive process. The thermodynamic minimum amount of energy primarily depends on the feed water TDS, feed water recovery, and the chemistry of the water and precipitates that may form (NRC, 2008; Lienhard et al., 2017; Shah et al., 2022). An actual desalination system will require greater amounts of energy due to inefficiencies in motors and pumps, fluid friction, and heat losses and inefficiencies in heat transfer. Desalination of PW is especially energy intensive. For example, Shah et al. (2022) report that the minimum energy to desalinate seawater with 50% feed water recovery is 1.11 kWh/m^3, whereas the same recovery of PW containing 204,000 mg/L of TDS requires 9.26 kWh/m^3; in other words, 8.3 times more energy is required even though the salinity is only 5.8 times greater. Electrical, mechanical, and heat transfer inefficiencies will substantially increase the energy required for these processes. For example, Lienhard et al. (2017) calculate that the actual energy requirement to desalinate seawater by the RO process at 40% recovery is 2.3 kWh/m^3. The NRC (2008) stated that existing desalination technologies approach the practical energy minimum and that significant reductions in the energy to desalinate water are unlikely. Thus, claims of significant reductions in the amount of energy required to desalinate brackish, saline, or PW should be considered with a high degree of skepticism.

Perhaps the most important criterion regarding the effectiveness of PW treatment processes is the quality of the treated water. There are two general measures of the final quality of PW: its chemical composition and its toxicity. Cooper et al. (2021) suggest a general method of screening PW treated to a fit-for-purpose quality that includes both chemical analyses and toxicity testing. Their proposal includes lab testing of the treated water as well as environmental monitoring to identify possible long-term adverse outcomes of PW reuse. The toxicity of untreated Permian Basin PW was characterized by Hu et al. (2022) based on ecotoxicity assays. The greatest toxicity was attributed to the high salinity of untreated PW. It was found that high concentrations of NH_3, some heavy metals, and volatile organic compounds may also affect the toxicity of untreated PW to aquatic organisms.

All laboratory and pilot-scale desalination studies cited in this review report final TDS concentrations of less than 1,000 mg/L, and most report treated water TDS concentrations of less than 500 mg/L (see Table 20 for examples), the recommended concentration for public water supply under the federal Safe Drinking Water Act (SDWA). Chemical analyses of PW treated by a number of different technologies have demonstrated that Permian Basin PW can be treated to a quality that comfortably meets numeric SDWA standards (Ghurye et al., 2021; Tarazona et al., 2024b; Delanka-Pedige et al., 2023; Delanka-Pedige et al., 2024; Scanlon et al., 2020a; Van Houghton et al., 2024). Two constituents that are incompletely removed by some thermal processes are ammonia (NH_3) and boron (B). Interestingly, neither constituent is regulated under the SDWA. However, NH_3 can lead to taste and odor problems and may affect drinking water disinfection processes. Ammonia is toxic to some aquatic organisms, while boron can be toxic to plants. Both parameters are subject to rules under the New Mexico Water Quality Act (20.6.4 NMAC).

A frequent concern regarding PW is that there may be unknown constituents present in the treated water that are not covered by federal or state regulations. The procedure for protecting against this possibility is to conduct toxicity testing in which organisms or specific cell cultures are exposed to the treated water and their effect on their viability is measured, a procedure known as Whole Effluent Toxicity (WET) testing. Two thorough studies of the toxicity of treated Permian Basin PW have recently been reported by Tarazona et al. (2024b) and Delanka-Pedige et al. (2024).

Van Houghton et al. (2024) reported that membrane distillation reduced the TDS of Permian Basin PW to less than 500 mg/L, and that the treated water met all primary and secondary SDWA standards. Furthermore, toxicity testing of the treated water found no residual cytotoxicity nor evidence of oxidative stress in aquatic organisms.

Tarazona et al. (2024a) conducted chronic and acute WET testing of treated water from a low temperature pilot-scale distillation process. The distillate, with a TDS of 475 mg/L, was found to exhibit some toxicity to test organisms due to low concentrations of NH_3, volatile and semi-volatile organic compounds, and trace metals including Cd, Cu and Cr. A follow-on lab study was done in which the distillate was polished by contacting with GAC and zeolite to remove NH_3, trace organics, and trace metals (Tarazona et al., 2024b). The indicator organisms used consisted of a freshwater algae (*Raphidocelis subcapitata*), a water flea (*Ceriodaphnia dubia*), zebrafish embryo (*Danio rerio*), and a marine bacteria (*Vibrio fischeri*). In addition to simple viability, the fetal heartbeat of zebrafish embryos was monitored to determine signs of stress. Each organism was subjected to long-term chronic tests and short-term acute tests. The study found that after the distillate was treated by granular activated carbon adsorption and zeolite ion exchange, it exhibited no toxicity for the *R. subcapitata, C. dubia,* and *D.rerio*, and the effects on the marine bacteria, *V. fischeri*, were reduced to 19%. It will be important to confirm these results in other studies. The research demonstrated the value of a holistic approach to PW treatment. Perhaps more importantly, it demonstrated that the treated water can meet stringent water quality standards including toxicity limits that would permit its reuse.

A study of membrane distillation of PW compared the performance of photocatalytic membrane distillation (PMD) and vacuum membrane distillation (VMD) with and without post-treatment UV disinfection. The feed water and treated water were subjected to analyses of inorganic constituents and non-targeted and targeted organic compounds (Delanka-Pedige et al., 2024). The results were compared to a variety of categories associated with human health including oral ingestion, genotoxicity and mutagenicity, endocrine disruption, and developmental health as well as comparison with measures of environmental threats including acute and chronic aquatic toxicity, environmental persistence, and bioaccumulation. Sixty-five compounds were identified in the feed water for which toxicity predictions could be made based on either actual toxicity data or theoretical predictions. The threat of each compound was characterized as very high (VH), high (H), medium (M), low (L) or inconclusive (I). The number of compounds in each category in the feed water and treated water are summarized in Figure 45. The results showed good removal of most toxicants by both VMD and photocatalytic membrane distillation treatment. Perhaps the most significant contribution of the study was its use of several different measures of toxic threats to both humans and the environment to characterize the toxicity of PW treated by two treatment processes.

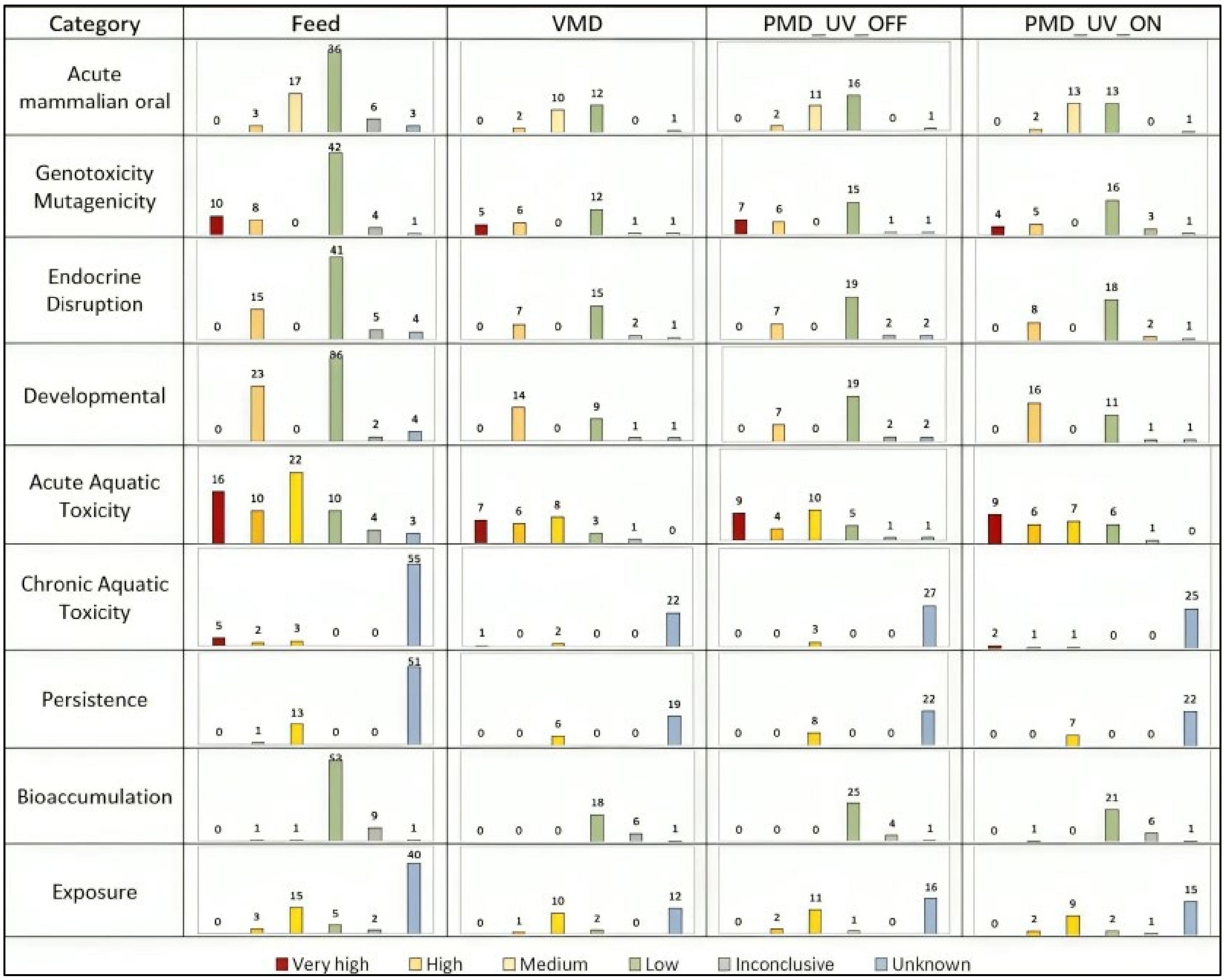

Figure 45. Number of compounds identified with varying risk factors in Permian Basin produced water (Feed), after vacuum membrane distillation (VMD), after photocatalytic membrane distillation without UV (PMD_UV_OFF), and after photocatalytic membrane distillation with UV disinfection (PMD_UV_ON) (Delanka-Pedige et al., 2024).

There is considerable uncertainty regarding the cost of treating Permian Basin PW, due in large part to the lack of pilot-scale demonstration projects, although there have been a few projections of the costs of treating PW from other regions. Even these projections are largely based on modeling studies using engineering process models rather than estimates based on field-scale pilot studies or from full-scale plant operation.

For a point of reference, the current cost of desalinating seawater to drinking water quality is reported to range from \$1.7 - \$9.5 /kgal (\$0.45 - \$2.41/m^3) (Ziolkowska, 2015; WateReuse Association, 2012) with a global average cost of \$3.5/kgal (\$0.9/m^3) in 2019 (Eke et al., 2020). These costs include the capital costs of designing and building the plant (capital expenditures, CAPEX) and operating and maintenance (O&M) costs over the lifetime of the plant (OPEX). The wide range in costs is due in part to economies of scale for large plants and inconsistent data reporting for desalination plants, particularly those in other countries. As noted, there are substantial differences in the quality and chemistry of PW from different O&G basins, which result in wide variation in the costs of treatment. Furthermore, projecting costs of desalinating Permian Basin PW based on the cost of desalinating seawater is not realistic because the technologies and constraints are so different.

While there are several studies reporting the cost of desalinating PW, most are for waters that have lower salinity than those from the Permian Basin and are based on RO, a process that is not feasible for treating PW from the Permian Basin. Sanchez-Rosario and Hildenbrand (2022) reviewed the literature on PW desalination and reported costs ranging from \$0.11/bbl to \$30/bbl (\$2.26/kgal to \$710/kgal, \$0.60/m^3 to \$190m^3) for PW from the Bakken Shale and Permian Shale; however, their review had few details on the technologies used or the specific water quality that was treated. They also discussed the possibility of recovering commodity metals from PW and focused on lithium. They reported that the minimum concentration of lithium in a brine solution that could be economically recovered was 180 mg/L based on an assumed PW treatment cost of \$2.32/bbl (\$55/kgal, \$15/m^3). The mean lithium concentration reported by Jiang et al. (2022b) was 22.4 mg/L for Permian Basin PW (see Table 20). Thus, even if a PW treatment plant was operated at 75% feed water recovery, the lithium concentration in the waste concentrate would be less than 90 mg/L, too low for economic recovery. Other elements that might have economic value included calcium, cobalt, magnesium, manganese, nickel, potassium, sodium, and strontium (Smith et al., 2024).

A study done for the NMED cited legislative testimony that estimated costs of treating Permian Basin PW ranging from \$1.12/bbl to \$2.14/bbl (\$7.00/m^3 to \$13.50/m^3) depending on the size of the treatment plant (NMED and ERG, 2024). Tavakkoli et al. (2017) developed a Techno-Economic Assessment (TEA) model of membrane distillation for desalinating Marcellus Shale PW with salinity similar to that from Permian Basin PW. They reported a cost of \$22/kgal (\$0.92/bbl, or \$5.80/m^3). The principal variables affecting the cost were the salinity of the water and the cost of energy. If waste heat could be used for the process, such as that from a gas compressor station, the cost could be as little as \$2.80 /kgal (\$0.12 /bbl or \$0.74/m^3). Eyitayo et al. (2023b) cite costs for treating PW from the Marcellus Shale that range from \$150/kgal (\$6.50/bbl or \$41/m^3) to \$260/kgal (\$11.00/bbl or \$69/m^3) compared to \$23/kgal (\$1.00/bbl or \$6.30/m^3) to \$60/kgal (\$2.50/bbl or \$16/m^3) for deep well injection.

This brief review shows that there are significant uncertainties in the technologies and costs of PW desalination. Though the costs are unknown at present due to the very high salinity, complicated chemistry, and waste management challenges, they will be greater than the cost of seawater desalination. The O&G industry is very cost conscious; therefore, in order for PW desalination to become widely practiced, it must be less expensive than other disposal methods. Alternatively, other financial incentives must be available, perhaps in the form of subsidies to cover part of the cost for the desalinated water. It is not clear that PW desalination technologies for treating Permian Basin PW have reached a level of maturity to justify investment in full-scale plants, nor is PW desalination and reuse economically justified at present. However, rapid advances are being made in the science and treatment technologies of PW by public and private research and development programs in Colorado, New Mexico, Texas, and elsewhere.

Conclusions

Produced water from O&G production presents a remarkable conundrum to water managers in New Mexico. On one hand, it constitutes a very large volume of water that is not subject to New Mexico law regarding water rights. Approximately 324,000 AF of PW were generated in 2024, 98% of which was in the Permian Basin of southeastern New Mexico. Reuse of PW is not allowed for any purpose outside of the O&G industry. In recent years, the industry has been able to use PW for fracking, which has nearly eliminated demand for fresh water for this purpose. Roughly 10% of the PW generated in New Mexico, 29,400 AF in 2024, was reused for fracking. However, virtually all of this water returns to the surface as flowback, so its use for fracking does not constitute disposal. According to reports submitted to NMOCD, slightly less than half of the PW is reused for EOR, while the rest is disposed of in SWD wells, though PW disposed of by evaporation or transported to Texas is not reported. The large volume of PW disposed of in deep SWD wells has caused increased seismicity in the Permian Basin, which has led regulatory agencies to limit the approval of new SWD wells, and have considered placing further restrictions on the maximum injection pressures that can be used. These constraints have led to concerns that limits on PW disposal may constrain future oil and gas production in the basin (Scanlon et al., 2020a).

Although the very large volume of PW generated each year presents a waste management challenge, it also may constitute a source of water that could supplement existing limited fresh water supplies in a very dry region of the country if it were treated to a quality that would permit its reuse. However, the extremely high salinity of PW, its corrosivity, and the presence of hazardous, toxic, and radioactive constituents present formidable technical and financial obstacles to its treatment reuse. This can be illustrated by comparing desalination of PW to that of seawater. Whereas over 21,000 seawater desalination projects have augmented fresh water supplies for coastal communities throughout the world (Eyl-Mazzega and Cassignol, 2022), reported experience with desalination of extreme salinity PW is limited to a few pilot tests, none of which has operated for more than eight months. The major differences between seawater and Permian Basin PW desalination are: (1) the average salinity of Permian Basin PW is three times greater than seawater and much of it is even more saline; (2) the very high salinity means that exotic materials must be used to withstand the higher corrosion potential; (3) PW chemistry is more difficult to desalinate because of high concentrations of scale-forming minerals; (4) desalination of PW produces waste concentrates with extremely high salinity, from two to four or more times greater than the feedwater salinity, with a corresponding increase in the concentrations of hazardous, toxic, and radioactive constituents that may complicate disposal; (5) uncertainty about the viability and long-term performance of PW desalination technologies; and (6) the cost of desalinating PW will be high, certainly greater than the cost of seawater desalination.

Recent analyses of Permian Basin PW chemistry have not detected elevated concentrations of any constituents that cannot be removed by existing treatment methods. A growing amount of experience with laboratory and field-scale pilot treatment processes has demonstrated the ability to treat PW to a high quality. While there has been some interest in recovering critical minerals such as lithium, magnesium, and manganese from Permian Basin PW, this has not been demonstrated in either laboratory or pilot testing projects. If feasible, recovery of these constituents would offset some of the high treatment costs.

The review presented in this section demonstrates that remarkable increases in knowledge about the volumes of PW generated and its quality, chemistry, and toxicity have been achieved in recent years. Laboratory and pilot-scale projects have identified several promising treatment technologies. Whereas membrane processes such as RO may be applicable for treating PW from the San Juan Basin, the very high salinity of PW from the Permian Basin means that thermal processes are most suitable for these waters. Studies of desalinated PW have shown that it can produce high quality water containing chemical constituents at concentrations below the most stringent standards for reuse. Furthermore, testing of the treated water shows that it can pass a variety of toxicity tests for aquatic insects, fish, cell cultures, and other measures of toxicity. Currently, the ability to desalinate large volumes of PW over long time periods (years or longer) has not been demonstrated.

The increasing risks of induced seismicity as a result of deep well injection of large volumes of PW is well documented and has led to concerns that future cost increases and limits on the disposal of PW may constrain future O&G development in the Permian Basin. This has caused increased interest in PW treatment and reuse by the O&G industry in the form of sponsoring fundamental academic research as well participating in field-scale pilot testing of new and innovative treatment technologies. Projections on PW treatment costs vary over a factor of ten between the lowest and highest cost estimates. There are two conclusions that can be reached from these studies. First, the estimated cost of desalinating PW to a fit-for-purpose use such as irrigation or discharge to the Pecos River to augment water delivery to Texas is orders of magnitude greater than the cost of purchasing water on the open market. Second, the projected costs of desalinating PW appear to be similar to but greater than the current cost of disposal in SWD wells. Disposal costs will increase if concerns about induced seismicity lead to more stringent regulations on the volumes and pressures that can be used for deep well disposal of PW. Improved estimates of costs of treatment will depend on the results of field-scale pilot studies.

Eyitayo et al. (2024) posed the question: Why is industry hesitant to implement full-scale reuse of PW? The authors identified five issues that constrain PW treatment and reuse:

- Environmental challenges. The high TDS concentrations in PW will require extensive treatment before it can be reused. A further challenge is management and disposal of the wastes generated by treatment processes.
- Technical challenges. The high TDS and complex chemistry of PW challenge current desalination technologies. Three especially notable issues that must be addressed are management of scale formation on membrane and heat transfer surfaces, the need to use expensive corrosion resistant materials, and the high energy requirements for desalination.

- Economic challenges. Both the capital and operating and maintenance (O&M) costs of treatment are higher than for disposal in SWD wells.
- Legal and regulatory measures. Current regulations regarding PW reuse are very stringent in most states, in part because of uncertainties regarding its hazardous and toxic characteristics. Eyitayo et al. (2024) argue in support of legislative reform to ease permitting for reuse based on improved knowledge of PW characteristics, new developments in PW treatment, and more rigorous monitoring and enforcement programs.
- Social challenges. There is considerable public opposition to PW reuse due to lack of public understanding of its quality and performance of treatment systems as well as industry reluctance to release confidential information. Public distrust is also fostered by the correlation between subsurface injection of PW induced seismicity as well as general mistrust of the fossil fuel industry.

While reuse of large volumes of PW outside of the O&G industry could have a beneficial impact on water resources in New Mexico, the cost and complexity of treating it to a quality suitable for reuse are too high for this to occur at present in the Permian Basin. There are two possible scenarios under which large-scale PW treatment and reuse might occur. The first scenario would be if improvements in PW desalination can reduce the cost of treatment and waste management so that treatment and reuse is less expensive than the cost of PW disposal in SWD wells. The other possible scenario is that regulatory limits on deep well injection would drive up the cost of disposal. For either scenario, the avoided cost of disposal would provide a strong incentive for PW reuse.

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Conclusions

This review and analysis has considered the technical and regulatory feasibility of four unconventional water sources: wastewater reuse, stormwater capture and reuse, development and desalination of deep brackish groundwater, and treatment and reuse of produced water (PW) from oil and gas (O&G) development. While each alternative appears to be a possible source of large volumes of water, more detailed analysis and evaluation shows that each has substantial regulatory and/or technical challenges that will likely limit the magnitude of their contribution to the state's water resources. Because each project to develop any of these sources of water will be unique, it is not possible to generalize the costs of the water obtained nor to compare it to the costs of water conservation or acquisition of water from conventional sources, which generally will consist of purchasing existing water rights. Nevertheless, the cost of complying with regulations and developing unconventional resources to augment current supplies will be very high. The challenges and opportunities associated with each of the four unconventional sources described in this report are briefly summarized below.

<u>Wastewater Reuse:</u> While wastewater reuse has received much national attention and is identified as a priority for development in the New Mexico 50-Year Water Action Plan, most large water utilities receive return flow credits for the treated wastewater they discharge. Under this circumstance, reusing the wastewater whether for NPR or DPR reduces this discharge and will require the utility to obtain additional water rights. If a utility does not receive return flow credits, they should determine whether they can apply for them. If they are not able to receive return flow credits, wastewater reuse may be a way of increasing their water supply because it will not require obtaining additional water rights.

Currently New Mexico does not have regulations that address wastewater reuse for either NPR or DPR applications, although the NMED has published guidelines for above ground non-potable wastewater reuse. Since regulations do not exist, planning a DPR project is difficult because of uncertainties regarding the degree and type of treatment needed, staffing requirements for plant operators, and monitoring requirements. An example is described where the Village of Cloudcroft designed and built a DPR project that included more treatment processes than required for DPR systems in other states, which increased the cost and complexity of the treatment plant. This illustrates the need for DPR regulations in New Mexico.

<u>Recommendations:</u>

- The NMED should develop rules governing both NPR and DPR to facilitate implementation of water reuse where it is appropriate. These rules need to address the required level of treatment, staffing requirements, monitoring requirements, implementation of a pre-treatment program to prevent hazardous constituents from entering the wastewater collection system, and implementation of a public participation program to assure acceptability of the reuse system.
- The NMED should modify water and wastewater plant operator training and certification programs to include training on advanced treatment processes for communities that incorporate potable reuse.

- Water utilities should evaluate their water rights portfolios and contact the State Engineer to determine if they receive return flow credits. If they do not, they should conduct an analysis to determine whether wastewater reuse may be feasible for augmenting their water supply. This analysis should determine the costs of building and operating a reuse system and compare it to the cost of acquiring new sources of watering. It should also consider whether the community has the financial resources and technical expertise to manage a complex system reliably and to comply with stringent regulatory requirements.

Stormwater Capture and Reuse: Although there is widespread national interest in stormwater capture and reuse to augment community water supplies, the regulatory and hydrologic conditions in New Mexico are different than most other regions in the country, which make this alternative generally impractical. The most important difference relates to water rights; once runoff leaves an individual's property it becomes subject to state water law. This means that a water right is required if stormwater is retained for longer than 96 hours. This requirement is to assure that runoff to streams and rivers provides water for downstream users and downstream states in accordance with requirements of Interstate Stream Compacts. Stormwater flows also provide water for environmental services that support aquatic and riparian environments.

One of the consequences of the 96-hour rule is that nearly all dams to control urban stormwater are "dry dams" that are not designed for long-term retention of water. Thus, they do not have gated outlets, an impervious core, and do not meet geotechnical design standards to enable long-term retention of water. Furthermore, modifying existing dams to provide both flood protection and water storage for later use would require raising the dam and acquiring additional land around the reservoir to enlarge the inundation pool, a difficult and expensive task in developed urban watersheds. An analysis is presented that shows that in spite of common perception, the volume of stormwater from urban watersheds in New Mexico is relatively small.

There may be a few opportunities for constructing stormwater capture and reuse projects at some locations. Desirable characteristics include: locations in which stormwater retention does not impact downstream users or interstate compact deliveries, undeveloped watersheds where acquiring surrounding land to raise the dam and increase the size of the inundation pool is feasible, and a location near a point of use. An example is described of a watershed and dam on the lower Rio Grande, north of Las Cruces, New Mexico that may meet these criteria.

Recommendations:

- Criteria should be developed to identify locations that may be suitable for stormwater capture and reuse. These may consist of undeveloped land near urban watersheds or existing stormwater reservoirs where enlarging the dam and reservoir pool may be feasible. Suggested criteria for watersheds where stormwater capture and reuse might be appropriate have been offered in this paper; however, other regulatory and technical characteristics should be identified as well.
- The U.S. Army Corps of Engineers maintains an inventory of all dams in New Mexico. This inventory should be subjected to a screening evaluation to identify dams that may offer opportunities for stormwater capture and reuse.

- Stormwater capture projects that appear feasible based on a preliminary evaluation should be subject to a more detailed analysis to include a hydrologic analysis to determine the volume of water that might be captured, the dam and reservoir modifications needed, and a first order estimate of the cost of these modifications. The study should also determine how the stormwater might be used, whether it be a source of water for irrigation or other use, or for infiltration to replenish groundwater as part of an underground storage and recovery system. Once design criteria have been developed, an economic analysis is needed to determine the economic viability of each project.

Brackish Groundwater Resources: While it appears that there is a large volume of brackish groundwater in New Mexico that can supplement water supplies without obtaining water rights, the magnitude and quality of the water resource is uncertain, as are the hydrogeological properties of the deep aquifers. Furthermore, it is likely that some rights will be required to offset impacts on overlying aquifers and surface waters even when pumping from deep brackish aquifers. Developing the resource will require drilling a large number of deep, expensive wells, and constructing long pipelines to transport the water to desalination plants and from there to its point of use. Desalination of the water will be difficult and costly due to the complex chemistry of brackish groundwater. Waste from the desalination process will be challenging to manage due to its large volume and possible characterization as a hazardous and/or radioactive waste. Most importantly, the resource is not sustainable therefore, proposed projects should be required to identify the human and economic consequences facing the community once the supply is exhausted.

A case study was presented for a proposed project in western Sandoval County that would use deep brackish groundwater as its primary source of supply. The proposed community would have an ultimate population of 309,000 people. A thorough hydrogeologic and engineering investigation was done, which included drilling two wells to depths of 3,850 ft (1,200 m) and 6,450 ft (2,000 m), construction and operation of a pilot desalination plant, and preparation of a detailed preliminary engineering report. The projected lifetime of the project ranges between 35 and 85 years, depending on two different estimates of hydrogeologic parameters and two growth scenarios for the urban development. Groundwater pumping for this community would result in an average decrease in groundwater head of 3,000 ft (910 m) in the deep aquifer over an area of 2,000 mi^2 (5,200 km^2), much of which is under Indian lands. Finally, groundwater modeling predicted that even though the deep aquifer is confined, the large amount of water pumped from it would eventually impact overlying aquifers and surface waters and therefore would require obtaining 4,500 AF/yr (5,600,000 m^3/yr) of water rights to offset these impacts.

Recommendations:

- More quantitative information is needed on the hydrogeologic characteristics of deep brackish aquifers, in particular the transmissivity, storativity, connection to overlying aquifers, and water quality in these formations. However, acquiring this information requires drilling and testing of deep wells, which is very expensive. Surface geophysical methods may be able to provide some of this information.
- Projects in which large volumes of groundwater will be diverted (200 AF/yr (250,000 m^3/yr) is suggested here) should be required to determine the hydrogeologic properties of the

formation conducting a pump test from an appropriately sited and constructed well. Impacts on overlying aquifers and surface waters must be identified.

- The duration of notices of intent (NOIs) to divert deep brackish groundwater should be clarified to facilitate planning of multiple projects diverting from the same formation with different filing dates of NOIs.
- The projected life of the water supply should be determined. Impacts of other projects developing water from the same aquifer must be included in this determination.
- Legal clarification is needed to determine how an impairment between nearby projects diverting water from the same deep aquifer will be resolved. A further complication will arise if the impairment extends beneath Indian lands that are not subject to New Mexico groundwater laws.
- The chemical characteristics of the desalination concentrate must be identified as well as the method of disposal of this waste.
- Deep brackish groundwater should be recognized as a non-sustainable source of supply and should not be allowed as the source of supply for municipal development unless a future sustainable source of supply is identified.

Reuse of Produced Water from Oil and Gas Development: A very large volume of wastewater is generated as a result of O&G production, greater than 324,000 AF (400,000,000 m^3) in 2024, that will increase in proportion to increased O&G production in the future. Slightly less than half of this water is used for enhanced oil recovery and the rest is disposed of by deep well injection in salt water disposal wells. An unknown volume of PW is disposed of by evaporation or transported across the border for disposal in Texas. Deep well injection of large volumes of PW has led to an increase in the number and magnitude of earthquakes in the Permian Basin as a result of induced seismicity. Recognition of the risks from induced seismicity have led to discussions of potential limits on this disposal method. The large volume of PW as well as the costs and challenges with its disposal have led to numerous research programs in New Mexico and elsewhere on the characteristics and treatment of high salinity PW for reuse. Treatment and reuse would supplement local water supplies as well as reduce the volume of waste requiring disposal.

The New Mexico Produced Water Act of 2019 included provisions that facilitate PW reuse including clarification that it is not under jurisdiction of the Office of the State Engineer, the water recovered is not associated with a water right, and that liability is transferred along with the water to the new user so that the O&G company that generated it does not have cradle-to-grave responsibility. While the act allows PW reuse, such treatment and reuse requires development of regulations and a permit process for this use; current regulations do not allow PW reuse outside of the O&G industry.

There has been much public opposition to PW treatment and reuse, due in large part to fears regarding the possible occurrence of unknown constituents with unusual hazardous and/or toxicity characteristics. A related concern is that current technologies are incapable of removing these contaminants. Recent studies of untreated PW quality from a large number of Permian Basin O&G wells have shown that although there are high concentrations of many regulated hazardous and/or radioactive constituents, often at concentrations that are orders of magnitude greater than regulations for subsequent use, there have been no detections of unexpected contaminants that cannot be removed by current treatment processes.

There is an increasing number of research programs to identify PW treatment technologies by both academic and industrial researchers. The high salinity of Permian Basin PW precludes desalination by conventional membrane processes such as RO, although there is some research on ultra-high pressure RO desalination. Therefore, most PW treatment methods are based on thermal treatment processes such as multistage flash distillation, multistage vapor recompression, high pressure vaporization, and membrane distillation. While these technologies are energy intensive, studies have demonstrated the ability of these processes to desalinate PW to a high quality including drinking water quality. Equally important, concerns about toxic effects from unidentified or unknown contaminants have been addressed through a variety of toxicity tests. These tests expose different aquatic organisms or cell lines to treated water and determine whether toxic effects are observed. Toxicity testing of desalinated PW has demonstrated that treatment methods have been developed that eliminate the toxicity of PW.

Although much progress has been made toward understanding the characteristics of PW and its treatment, full-scale treatment has not yet been demonstrated. A number of pilot-scale projects with flow rates of between 4,000 and 34,000 gal/d (15 m^3/d and 130 m^3/d) have been done but only for periods ranging up to eight months. In addition to its extremely high salinity and complicated water chemistry, the principal challenges of treating PW include: very high energy requirements, high concentrations of scale forming constituents, high corrosivity requiring use of expensive corrosion resistant materials, and the presence of hazardous and radioactive constituents that may complicate waste management and disposal. Pretreatment will likely be required to remove organic compounds that interfere with desalination processes, and post-treatment may be needed to remove constituents not completely removed by the desalination process such as ammonia and boron.

Recommendations:

- Pass regulations to allow treatment and reuse of PW outside of the O&G industry.
- Pass regulations governing intrastate and interstate transport and disposal of PW to quantify how it is managed and disposed of. This information is needed to support the economic viability of PW treatment and reuse projects.
- Continue research and development of PW treatment processes. Field-scale pilot testing is especially needed to develop information needed for the design, construction, and cost estimates of full-scale treatment plants.
- Require a comprehensive monitoring program of the treated water from pilot testing projects, including WET testing, to establish a record of performance that will address public concerns about the safety of treated PW.
- The O&G industry and regulatory agencies should initiate an information dissemination and public education program to demonstrate that treated PW can be reused safely with no unacceptable risk to human health or the environment. Allowing public access to PW treatment plants may be helpful. The objective of this activity would be to obtain public acceptance of PW treatment and reuse.

The complexity and energy requirements associated with treating PW for reuse are likely to result in costs of treated water that are orders of magnitude greater than the current cost of water for municipal, industrial, or agricultural uses. However, it does seem likely that this water can be treated at a cost that is less than that for disposal in deep SWD wells. Its treatment and reuse will thus have three benefits: (1) reducing PW disposal by deep well injection will reduce earthquake risks from induced seismicity, (2) treated water will provide a valuable resource to supplement existing supplies, and (3) the industry will benefit by reduced disposal costs and improved public relations.

Perhaps the most important point of the analyses in this paper is that each of the four sources of water is part of a complex hydrologic system that is subject to an intricate and interconnected network of regulatory, public and environmental health, hydrologic, economic, and infrastructure systems that must be explicitly recognized when considering development of the potential resource. Most of these constraints, especially the regulatory, health, economic, and infrastructure factors, are the results of many decades of evolution by water managers, planners, engineers, and consumers. They were developed to manage conventional surface and groundwater sources, and many of them present difficult challenges when applied to unconventional water sources. In order to develop these unconventional sources of water, innovative strategies will be needed to allow their use. Thus, the most important contribution of this paper is to begin to identify clearly, and semi-quantitatively characterize, the challenges associated with each in order to facilitate future innovation.