Texas Permian Future Generations

Public Comments on Land Application of Produced Water;
RPN 2026-006-309-OW

EXHIBIT 4
PART 2

Geology and hydrogeology

The Blaine Aquifer is a minor aquifer located along the eastern edge of the High Plains in North Texas (Figure 6-42). The aquifer is part of the Permian Blaine Formation, which is composed of red silty shale, gypsum, anhydrite, salt, and dolomite. The formation consists of cycles of marine and non-marine sediments deposited in a broad, shallow sea that once covered the southwestern United States. Saturated thickness reaches 300 feet in the aquifer, but freshwater saturated thickness averages 137 feet (Figure 6-43). Groundwater occurs primarily in solution channels and caverns within the beds of anhydrite and gypsum; dissolution of these minerals contributes to the overall poor quality of the water (Hopkins and Muller, 2011).

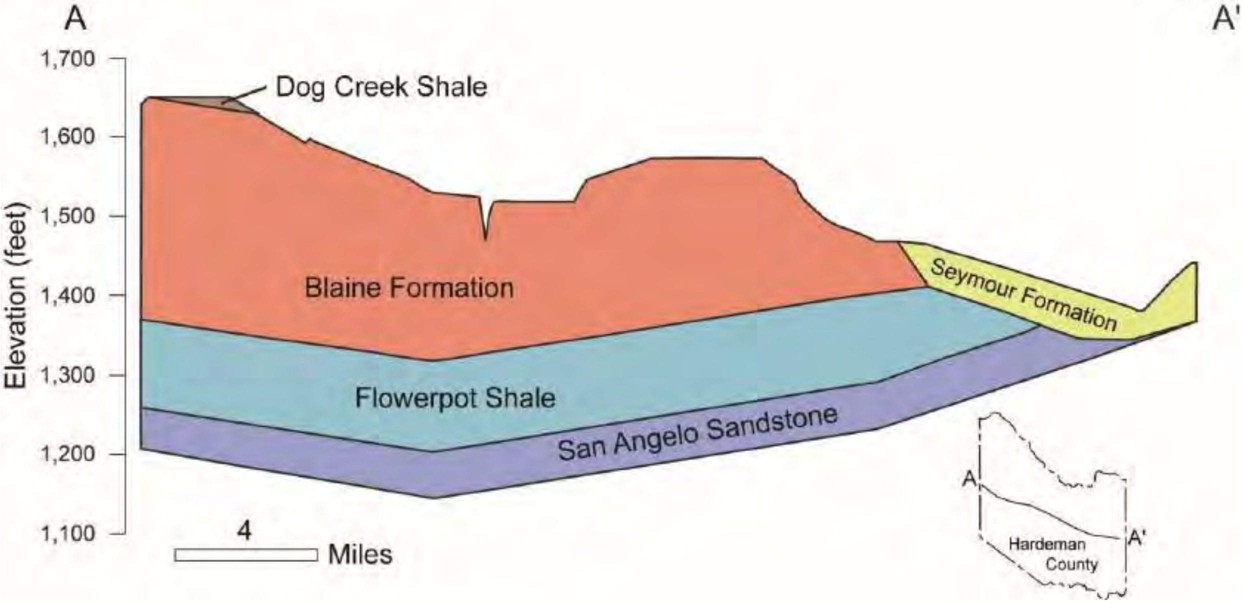


Figure 6-43. Structural cross-section of the Blaine Aquifer from the west to the east across Hardeman County (from Maderak, 1972).

Flows to surface water and other aquifers

Many springs originate from the Blaine Formation and contribute to surface water (Ewing and others, 2004). A summary of baseflow in the outcrop areas of the Blaine Aquifer is reported in Table 6-28. Groundwater availability model analysis estimates a total flow of 34,072 acre-feet per year from the Blaine Aquifer to the Seymour Aquifer and a total flow of 7,162 acre-feet per year from the Seymour Aquifer to the Blaine Aquifer (Table 6-29). While the Seymour Aquifer is made up of several separate "pods" with independent flow systems, in general the low sulfate concentrations in the Seymour Aquifer suggest that inter-aquifer flow is primarily from the Seymour Aquifer into the Blaine Aquifer (Ewing and others, 2004).

Table 6-28. Summary of groundwater flow from the Blaine Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Childress	462	3.2	0.8
Collingsworth	325	6.2	2.5
Cottle	501	5.4	2.2
Fisher	124	0.9	0.2
Foard	243	3.8	1.6
Hall	11	0	0
Hardeman	375	4.9	1
Jones	2	0	0
King	602	11.3	5.7
Knox	35	0.9	0.4
Nolan	7	0	0
Stonewall	437	2.6	0.3
Wheeler	85	2.1	1.1
Total	**3,209**	**41**	**16**

Table 6-29. Model estimates of inter-aquifer flows between the Blaine Aquifer and Seymour Aquifer.

Flow from	Flow to	Total flow (acre-feet per year)
Blaine Aquifer	Seymour Aquifer	34,072
Seymour Aquifer	Blaine Aquifer	7,162

Water quantity

Total storage in the Blaine Aquifer is estimated to be more than 171 million acre-feet. Recoverable storage in the aquifer is estimated to be between 25 and 75 percent of the total, about 42.9 million to 128.7 million acre-feet (Table 6-30).

Table 6-30. Total estimated recoverable storage in the Blaine Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Childress	18,000,000	4,500,000	13,500,000
Collingsworth	29,000,000	7,250,000	21,750,000
Cottle	22,000,000	5,500,000	16,500,000
Dickens	35,000	8,750	26,250
Fisher	15,000,000	3,750,000	11,250,000
Foard	5,900,000	1,475,000	4,425,000
Hall	2,500,000	625,000	1,875,000
Hardeman	10,000,000	2,500,000	7,500,000
Jones	880,000	220,000	660,000
Kent	490,000	122,500	367,500
King	24,000,000	6,000,000	18,000,000
Knox	810,000	202,500	607,500
Motley	110,000	27,500	82,500
Nolan	260,000	65,000	95,000
Stonewall	36,000,000	9,000,000	27,000,000
Wheeler	6,700,000	1,675,000	5,025,000
Wilbarger	1,400	350	1,050
Total	**171,686,400**	**42,921,600**	**128,764,800**

Water quality

Groundwater in the Blaine Aquifer is typically brackish. Although some wells contain slightly saline water, with total dissolved solids between 1,000 and 3,000 milligrams per liter, most contain moderately saline water, with total dissolved solids between 3,000 and 10,000 milligrams per liter, exceeding secondary drinking water standards for Texas (Hopkins and Muller, 2011). Sulfate values are also well in excess of the secondary drinking water standard of 300 milligrams per liter. Figure 6-44 shows the distribution of total dissolved solids in the Blaine Aquifer.

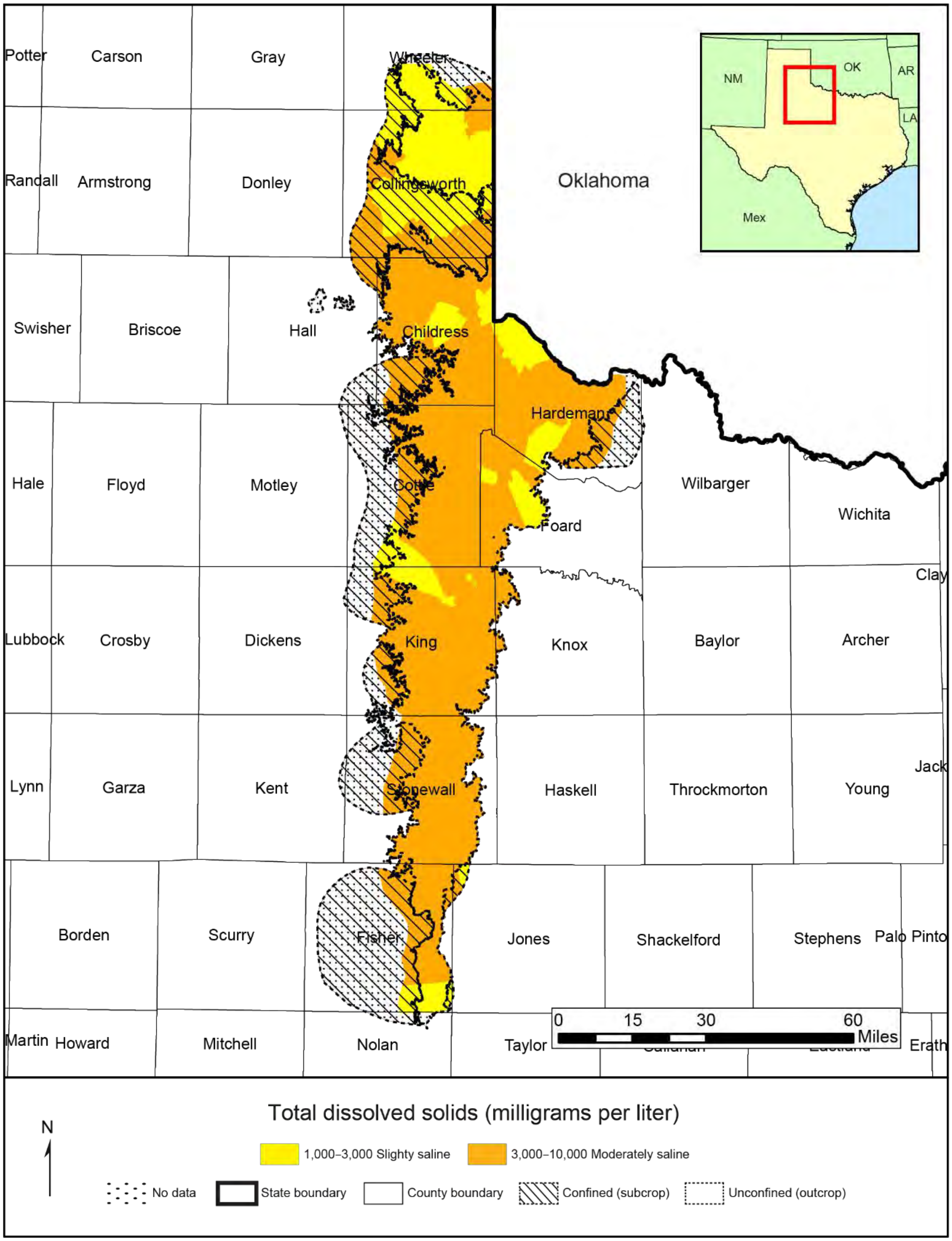


Figure 6-44. Total dissolved solids in the Blaine Aquifer.

6.11 Blossom Aquifer

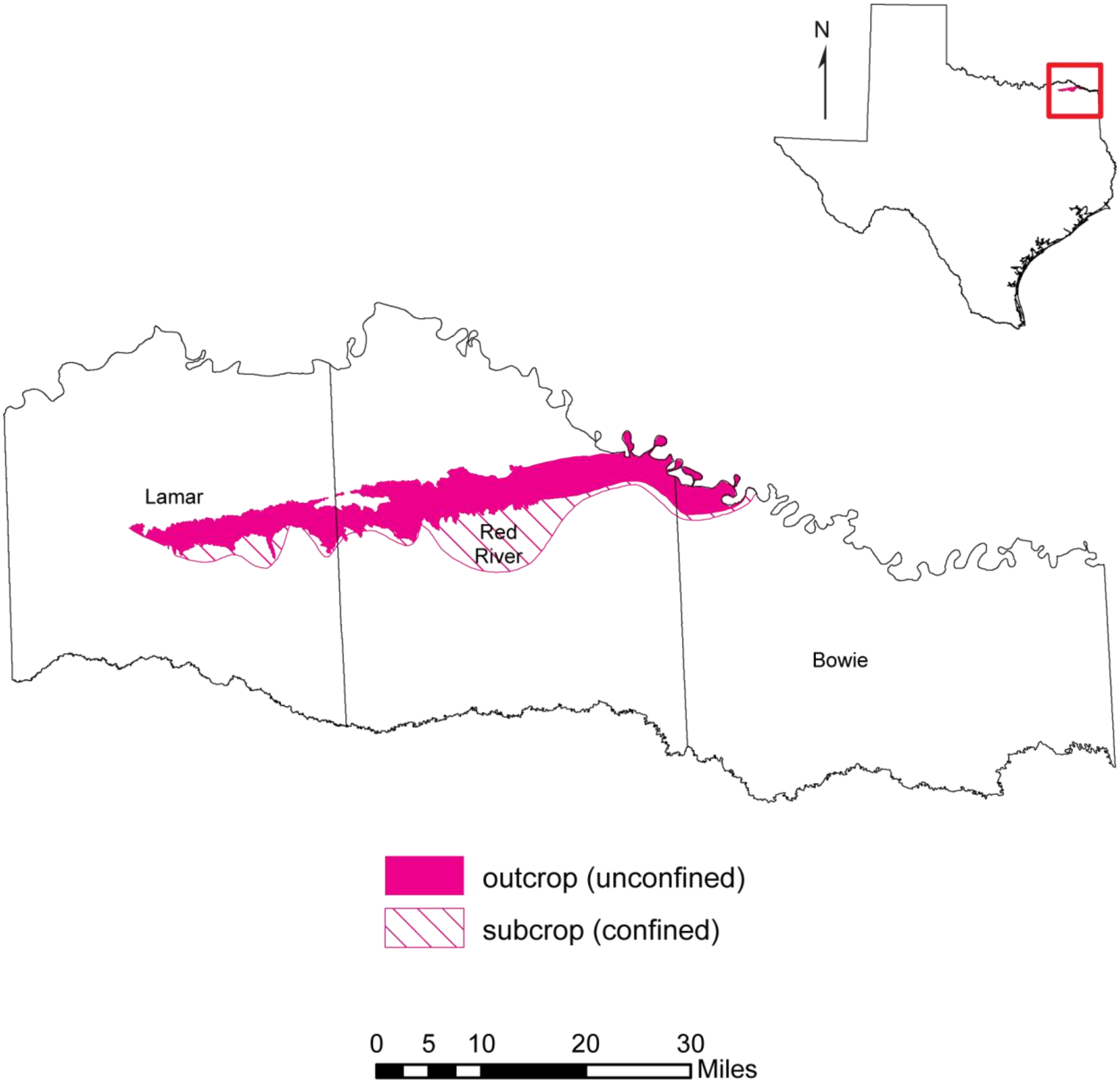


Figure 6-45. Extent of the Blossom Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 182 square miles
- Area of subsurface: 95 square miles
- Proportion of aquifer with groundwater conservation districts: 0 percent
- Number of counties containing the aquifer: 3

Geology and hydrogeology

The Blossom Aquifer is a minor aquifer located in Bowie, Red River, and Lamar counties in the northeast corner of Texas (Figure 6-45). The aquifer consists of the Blossom Sand Formation, composed of alternating sequences of sand and clay. In places, the aquifer is as much as 400 feet thick, although no more than about one-third of this thickness consists of sand, and freshwater saturated thickness averages 25 feet (Figure 6-46 and Figure 6-47).

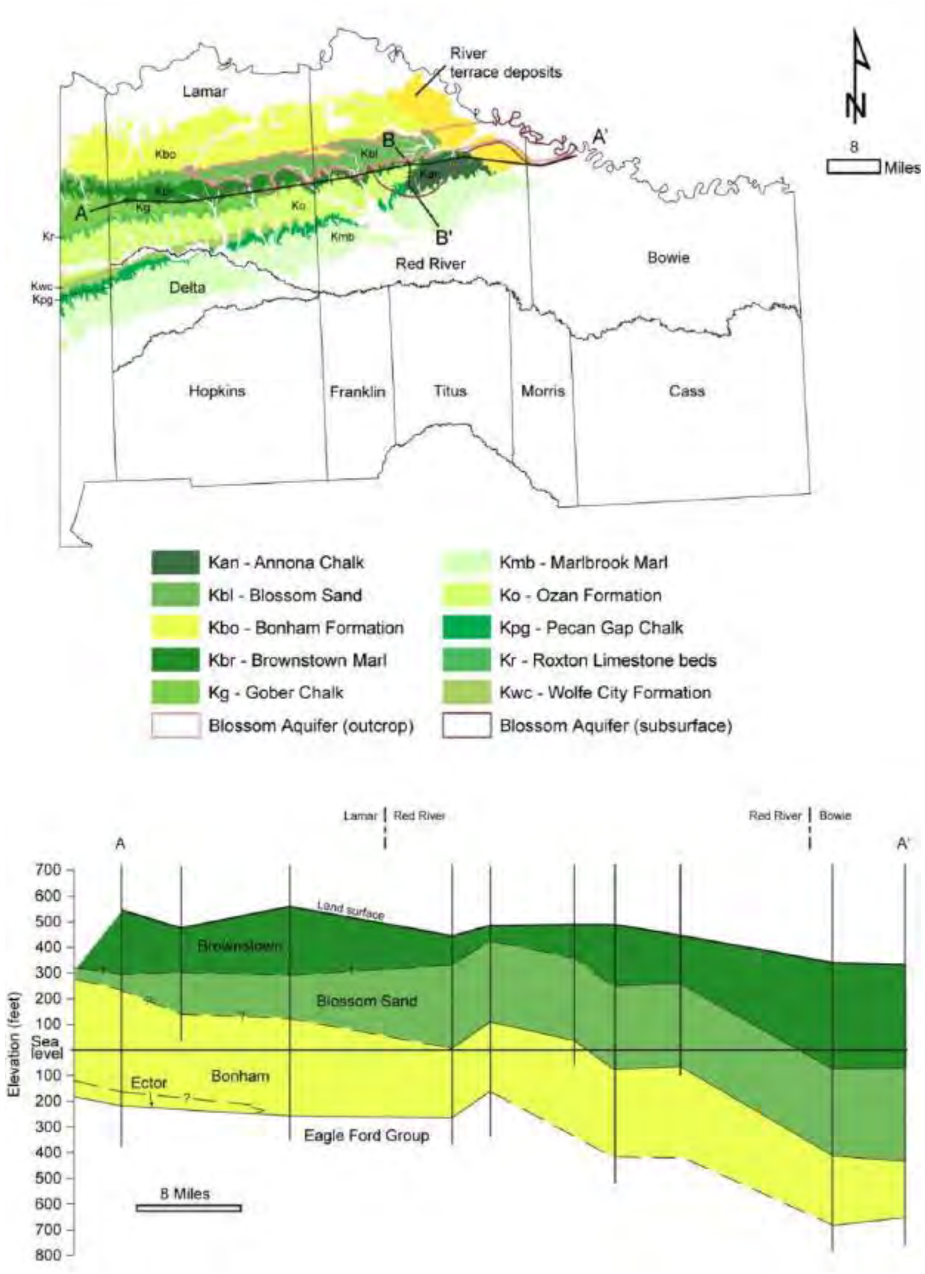


Figure 6-46. **East to west geologic cross-section along the Blossom Aquifer (modified from McLaurin, 1988).**

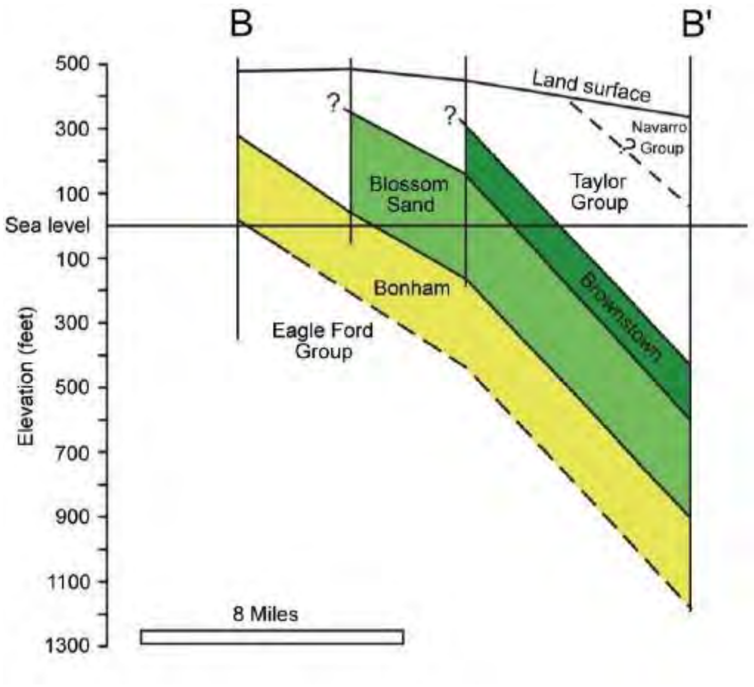


Figure 6-47. North to south geologic cross-section across the Blossom Aquifer (modified from McLaurin, 1988).

Flows to surface water and other aquifers

A summary of baseflow in the outcrop area of the Blossom Aquifer is reported in Table 6-31. Currently, there is no groundwater availability model for the Blossom Aquifer. The Blossom aquifer is separated from the underlying Trinity Aquifer by the shales of the Eagle Ford Group, which forms an effective aquitard between these systems (Kelley and others, 2014). No inter-aquifer flow is expected to occur between the Blossom Aquifer and the Trinity Aquifer or any other major or minor aquifer.

Table 6-31. Summary of groundwater flow from the Blossom Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Bowie	15	3.3	1
Lamar	48	3.6	0.3
Red River	119	13.3	1.3
Total	**182**	**20**	**3**

Water quantity

Total storage in the Blossom Aquifer is estimated to be more than 7 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 1.7 million to 5.3 million acre-feet (Table 6-32).

Table 6-32. Total estimated recoverable storage in the Blossom Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Bowie	910,000	227,500	682,500
Lamar	970,000	242,500	727,500
Red River	5,200,000	1,300,000	3,900,000
Total	**7,080,000**	**1,770,000**	**5,310,000**

Water quality

The Blossom Aquifer yields water of usable quality to wells located mostly in outcrop areas. However, in part of Red River County, slightly saline water, with total dissolved solids less than 3,000 milligrams per liter, extends underground for about 6 miles south of the outcrop (Figure 6-48). Groundwater in the aquifer is generally soft, slightly alkaline, and, in some areas, high in sodium, bicarbonate, iron, and fluoride. The water has a high sodium adsorption ratio and ranks high on the residual sodium carbonate index, which makes it unsuitable for irrigation.

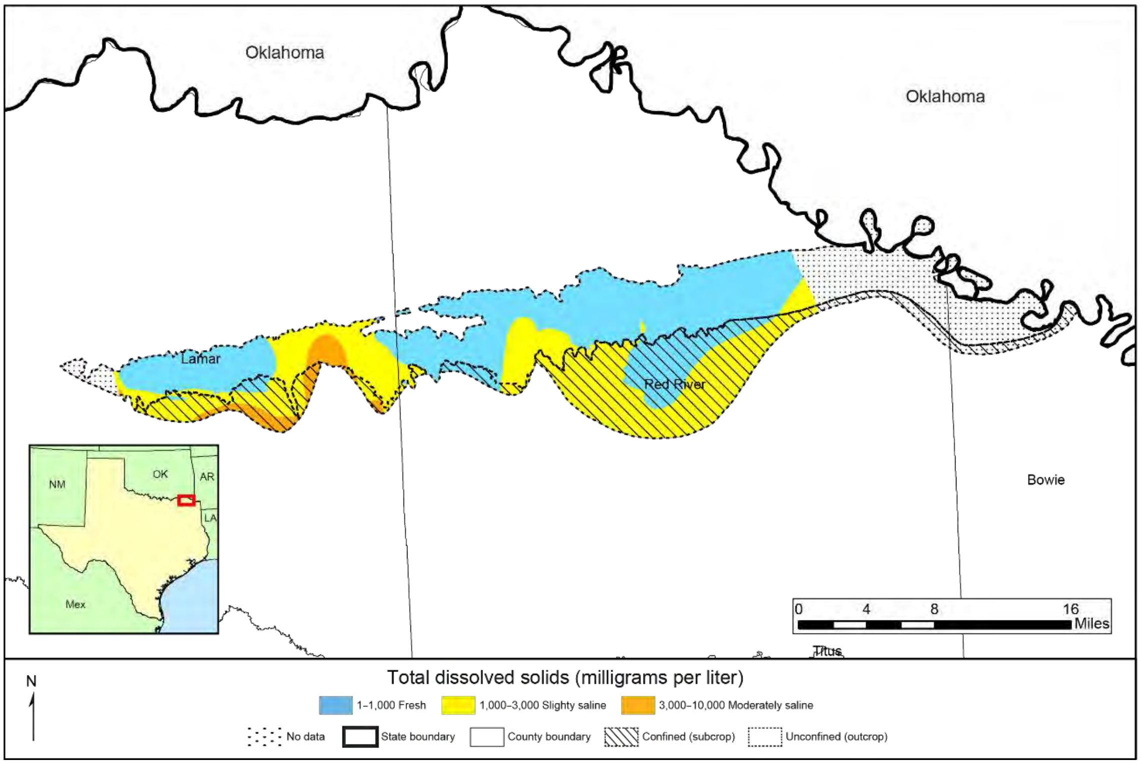


Figure 6-48. Total dissolved solids in the Blossom Aquifer.

6.12 Bone Spring-Victorio Peak Aquifer

Figure 6-49. Extent of the Bone Spring-Victorio Peak Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 713 square miles
- Proportion of aquifer within a groundwater conservation district: 100 percent
- Number of counties containing the aquifer: 1

Geology and hydrogeology

The Bone Spring-Victorio Peak Aquifer is a minor aquifer located in northern Hudspeth County and extending across the border into New Mexico (Figure 6-49). A cross-section of the aquifer is shown in Figure 6-50. Water occurs in dissolution features and along voids and fractures in two water-bearing limestone units, and the formation is locally very permeable. The estimated average effective recharge for the Bone Spring-Victorio Peak Aquifer in Hudspeth County is 4,035 acre-feet per year. Annual effective recharge is estimated at 5 percent of annual precipitation.

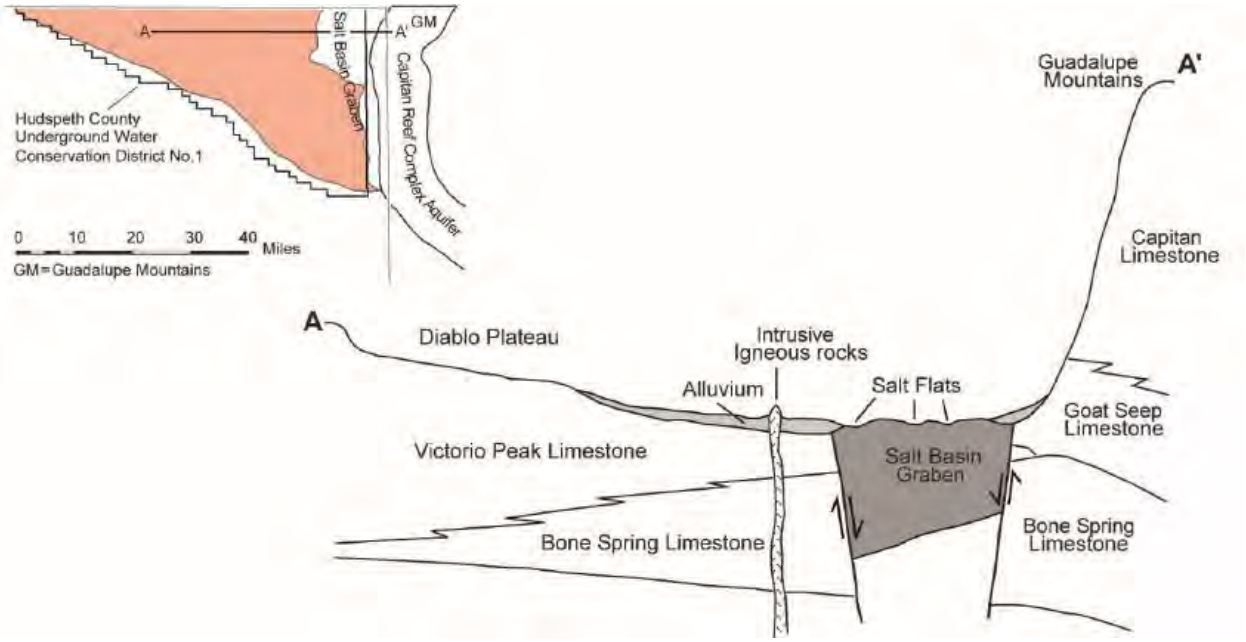


Figure 6-50. **Structural cross-section of the Bone Spring-Victorio Peak Aquifer in northeastern Hudspeth County (modified from Ashworth, 1995).**

Flows to surface water and other aquifers

The Bone Spring-Victorio Peak Aquifer naturally discharges to surface water. A summary of baseflow in the outcrop areas of the Bone Spring-Victorio Peak Aquifer is reported in Table 6-33

The Bone Spring-Victorio Peak Aquifer is not in direct contact with any other major or minor aquifers and consequently no inter-aquifer flow is expected to occur.

Table 6-33. Summary of groundwater flow from the Bone Spring-Victorio Peak Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Hudspeth	713	9.3	4.5

Water quantity

Total storage in the Bone Spring-Victorio Peak Aquifer is estimated to be 3.7 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 925,000 and 2.7 million acre-feet (Table 6-34).

Table 6-34. Total estimated recoverable storage in the Bone Spring-Victorio Peak Aquifer in Hudspeth County, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Hudspeth	3,700,000	925,000	2,775,000
Total	**3,700,000**	**925,000**	**2,775,000**

Water quality

Water quality in the Bone Spring-Victorio Peak Aquifer is generally slightly saline, with total dissolved solids of 1,000 to 3,000 milligrams per liter. In the Dell Valley area, total dissolved solids increase to 3,000 to 10,000 milligrams per liter (Figure 6-51). Water quality in this area appears to be controlled by two mechanisms: 1) groundwater flowing through the aquifer system and dissolving minerals along its flow path and 2) irrigation water concentrated by evaporation percolating down through the soil zone.

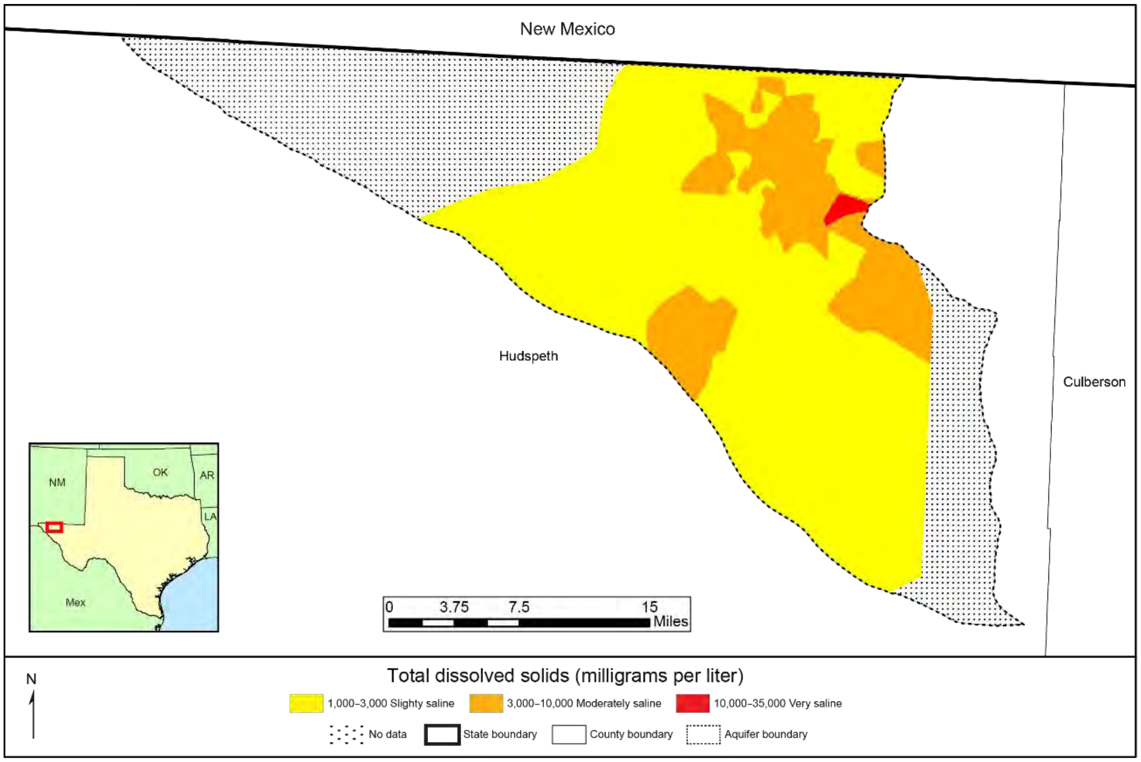


Figure 6-51. Total dissolved solids in the Bone Spring-Victorio Peak Aquifer.

6.13 Brazos River Alluvium Aquifer

Figure 6-52. Extent of the Brazos River Alluvium Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 1,057 square miles
- Proportion of aquifer with groundwater conservation districts: 85 percent
- Number of counties containing the aquifer: 13

Geology and hydrogeology

The Brazos River Alluvium Aquifer is a minor aquifer found along the Brazos River in east central Texas. The aquifer is as much as 7 miles in width and extends along 350 river miles from southern Bosque County to eastern Fort Bend County (Figure 6-52). Groundwater is contained in alluvial floodplain and terrace deposits, although the latter is not an appreciable source of water. The floodplain alluvium consists of fine to coarse sand, gravel, silt, and clay. These deposits have a complex geometry, with beds or lenses of sand and gravel that pinch out or grade vertically into finer material. In general, finer sediments occur in the upper part of the aquifer while coarser material occurs in the lower part.

The thickness of the aquifer ranges from negligible to 168 feet, with an overall average of about 50 feet (Figure 6-53). The aquifer is unconfined and is mainly used for irrigation. The water table generally slopes toward the Brazos River, indicating that the river is a gaining stream in most places. Recharge to the aquifer occurs from rainfall onto the aquifer outcrop and subsequent downward leakage to the saturated zone. Discharge from the aquifer occurs through evapotranspiration, discharge to the river, and withdrawals from wells. The majority of wells yield from 250 to 500 gallons per minute, though some wells can yield as much as 1,000 gallons per minute. The mean hydraulic conductivity of the aquifer is estimated to be 241 feet per day (Shah and others, 2007). The specific yield is estimated to be 0.15 (Cronin and Wilson, 1967). No significant water-level declines have occurred in the aquifer to date.

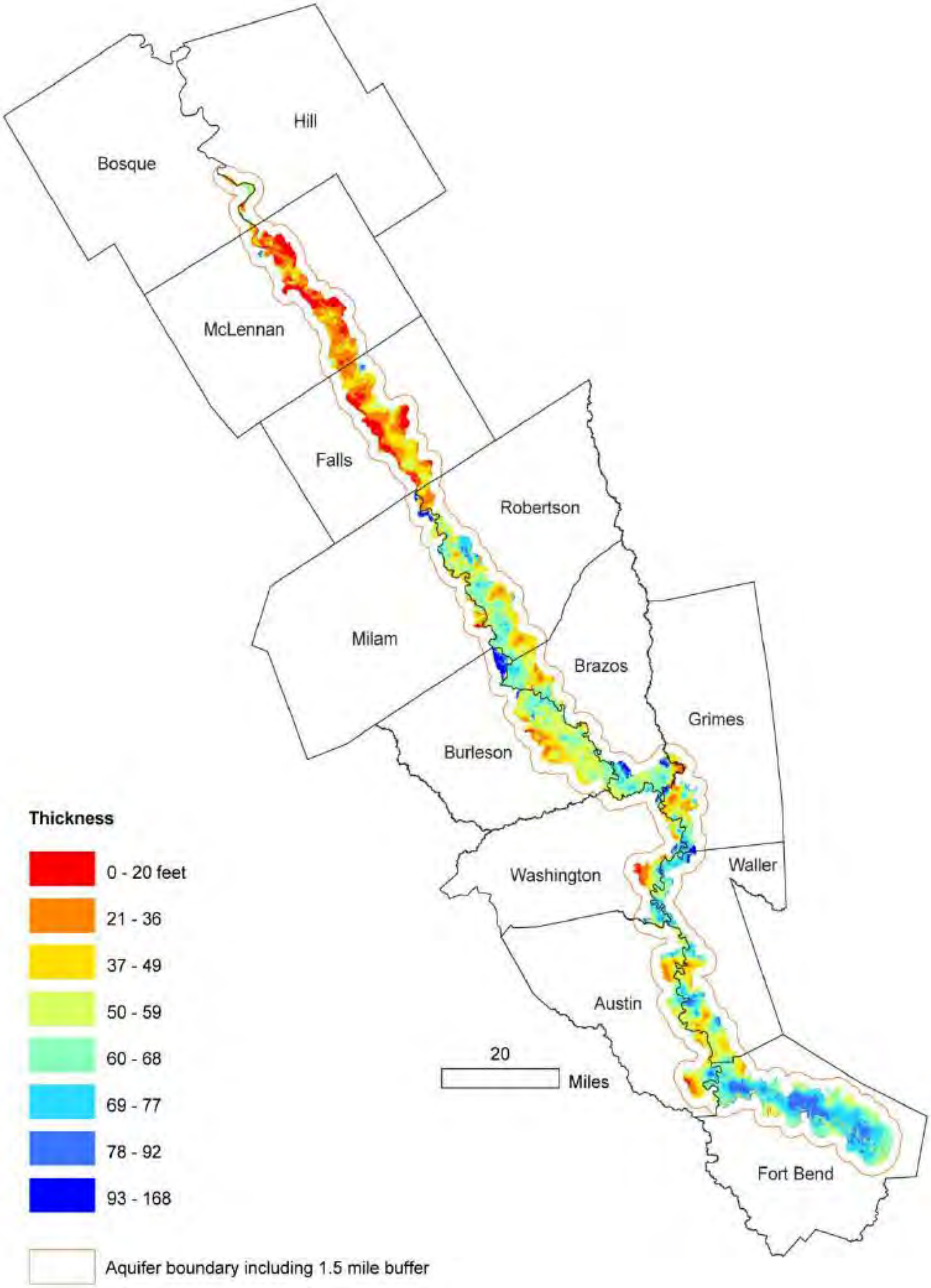


Figure 6-53. **Thickness of the Brazos River Alluvium Aquifer, Bosque County to Fort Bend County, Texas (from Shah and others, 2007).**

Flows to surface water and other aquifers

The Brazos River intersects the Brazos River Alluvium Aquifer, and there are several springs in the aquifer area. The aquifer also shows interaction with reservoirs and oxbow lakes in the area (Ewing and others, 2016). A summary of baseflow in the outcrop area of the Brazos River Alluvium Aquifer is reported in Table 6-35. Groundwater availability model analysis estimates a total flow to the Brazos River Alluvium Aquifer from the Carrizo-Wilcox Aquifer of 2,361 acre-feet per year (Table 6-36).

Table 6-35. Summary of groundwater flow from the Brazos River Alluvium Aquifer to surface water by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Austin	64	7.5	1.3
Bosque	6	0.2	0
Brazos	97	8.5	1.6
Burleson	129	9.1	1.6
Falls	113	5.3	0.7
Fort Bend	197	32.8	7.8
Grimes	43	3.1	0.4
Hill	4	0.1	0
McLennan	103	3.9	0.4
Milam	23	1.6	0.2
Robertson	132	9.3	1.1
Waller	98	11.1	2
Washington	47	3.5	0.7
Total	**1,056**	**96**	**18**

Table 6-36. Model estimates of inter-aquifer flows between the Brazos River Alluvium Aquifer and the Carrizo-Wilcox Aquifer.

Flow from	Flow to	Total flow (acre-feet per year)
Carrizo-Wilcox Aquifer	Brazos River Alluvium Aquifer	2,361

Water quantity

Total storage in the Brazos River Alluvium Aquifer is estimated to be more than 3 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 800,000 to 2.4 million acre-feet (Table 6-37).

Table 6-37. Total estimated recoverable storage in the Brazos River Alluvium Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Austin	220,000	55,000	165,000
Bosque	9,600	2,400	7,200
Brazos	290,000	72,500	217,500
Burleson	450,000	112,500	337,500
Falls	160,140	40,035	120,105
Fort Bend	1,010,000	252,500	757,500
Grimes	74,700	18,675	56,025
Hill	6,600	1,650	4,950
McLennan	90,000	22,500	67,500
Milam	36,700	9,175	27,525
Robertson	270,000	67,500	202,500
Waller	412,000	103,000	309,000
Washington	179,000	44,750	134,250
Total	**3,208,740**	**802,185**	**2,406,555**

Water quality

Water in the Brazos River Alluvium Aquifer is very hard and fresh to slightly saline, generally containing less than 1,000 milligrams per liter of total dissolved solids, but ranging to as much as 3,000 milligrams per liter in some wells (Figure 6-54). Only a small percentage of the aquifer area (1 to 2 percent) is at high risk of exceeding primary or secondary maximum contaminant levels. The northern aquifer extent is at risk of nitrate-N, gross alpha, barium, and arsenic primary maximum contaminant levels. High total dissolved solids dominate secondary maximum contaminant level exceedances (Reedy and others, 2011).

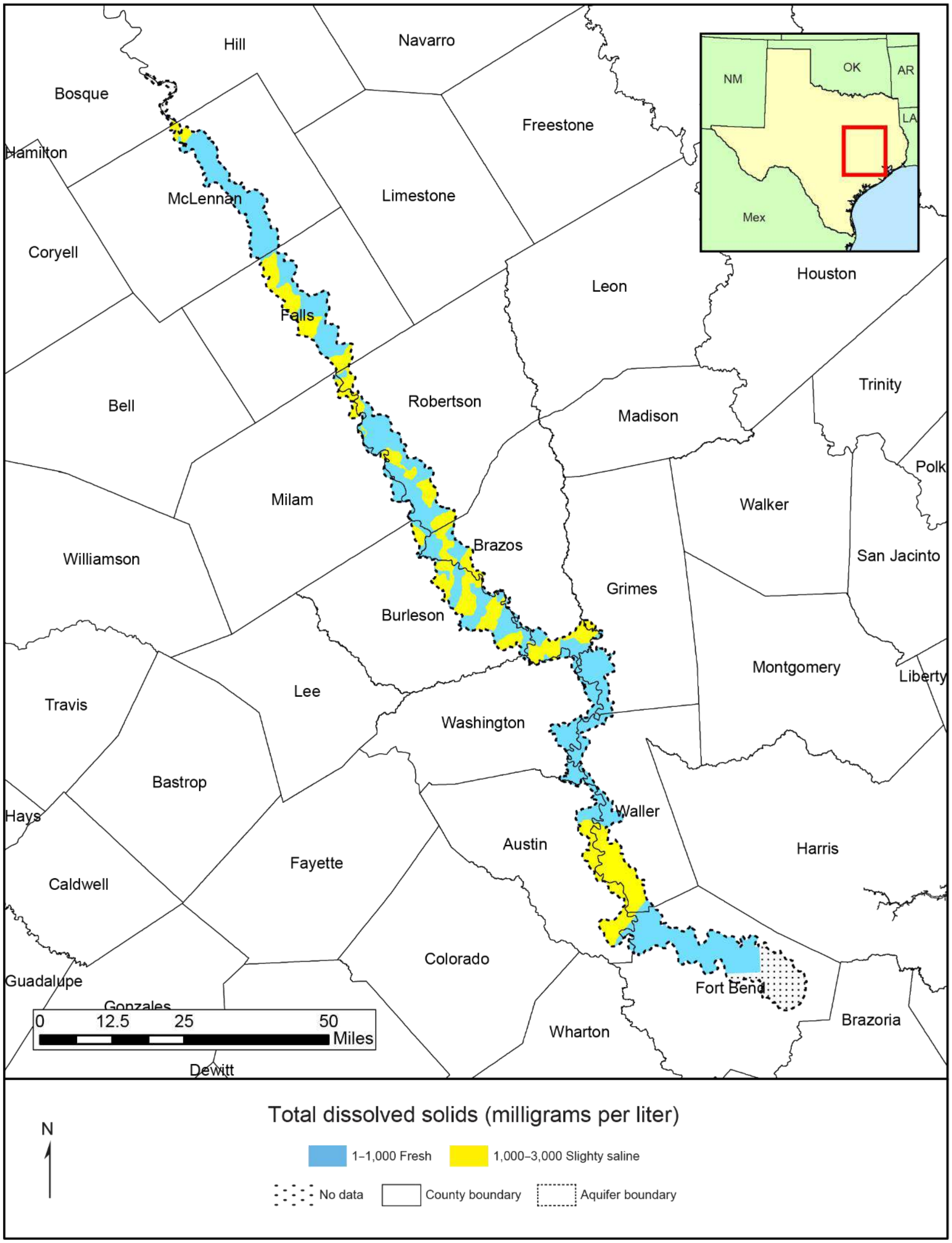


Figure 6-54. Total dissolved solids in the Brazos River Alluvium Aquifer

6.14 Capitan Reef Complex Aquifer

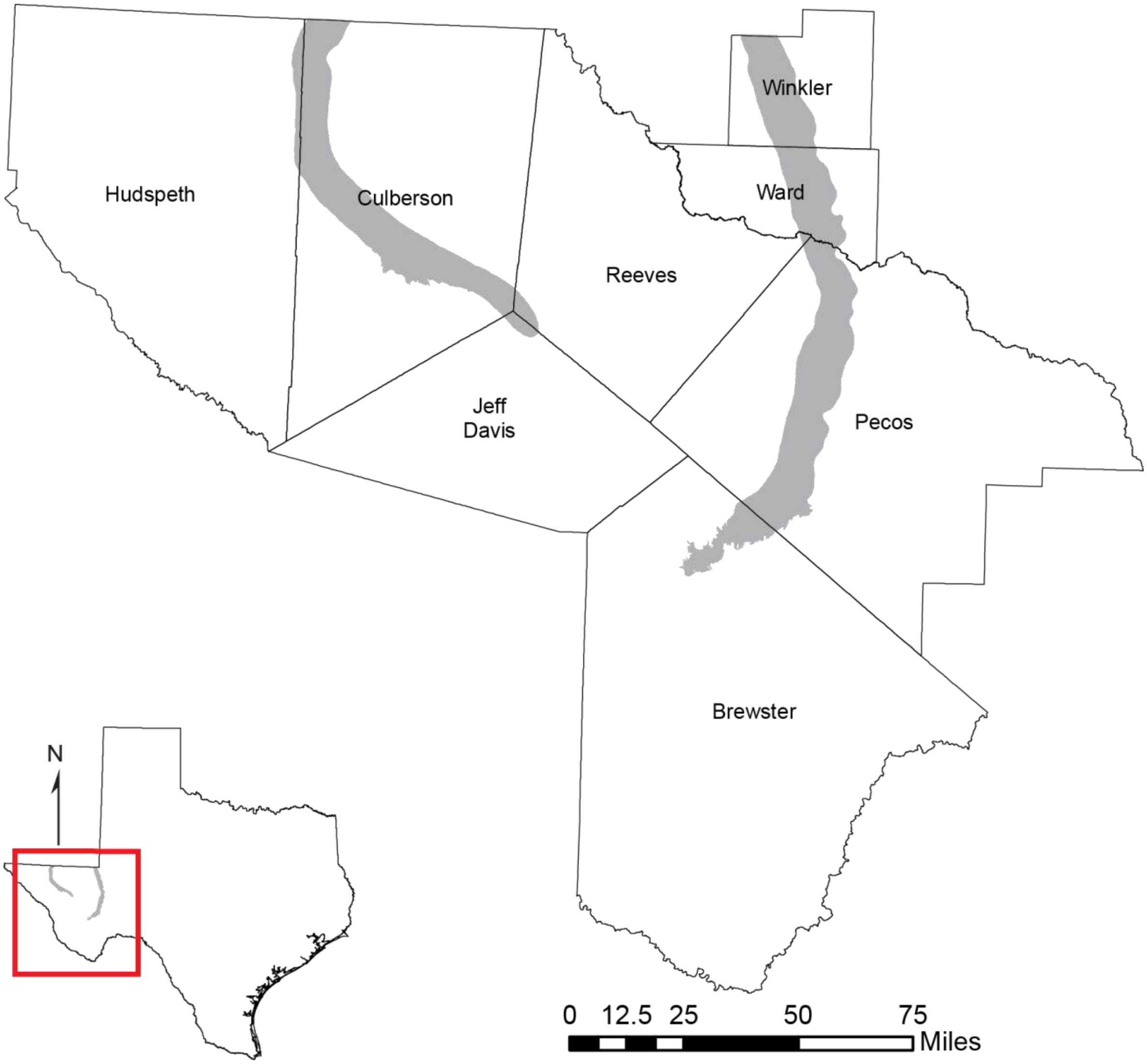


Figure 6-55. Extent of the Capitan Reef Complex Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 1,850 square miles
- Proportion of aquifer with groundwater conservation districts: 62 percent
- Number of counties containing the aquifer: 8

Geology and hydrogeology

The Capitan Reef Complex Aquifer is a minor aquifer located in Culberson, Hudspeth, Jeff Davis, Brewster, Pecos, Reeves, Ward, and Winkler counties (Figure 6-55). It is exposed in mountain ranges of far west Texas; elsewhere it occurs in the subsurface. The aquifer is composed of as much as 2,360 feet of massive, cavernous dolomite and limestone. Water occurs in solution cavities and fractures that are unevenly distributed in the water-bearing dolomite and limestone formations (Figure 6-56, Figure 6-57, and Figure 6-58).

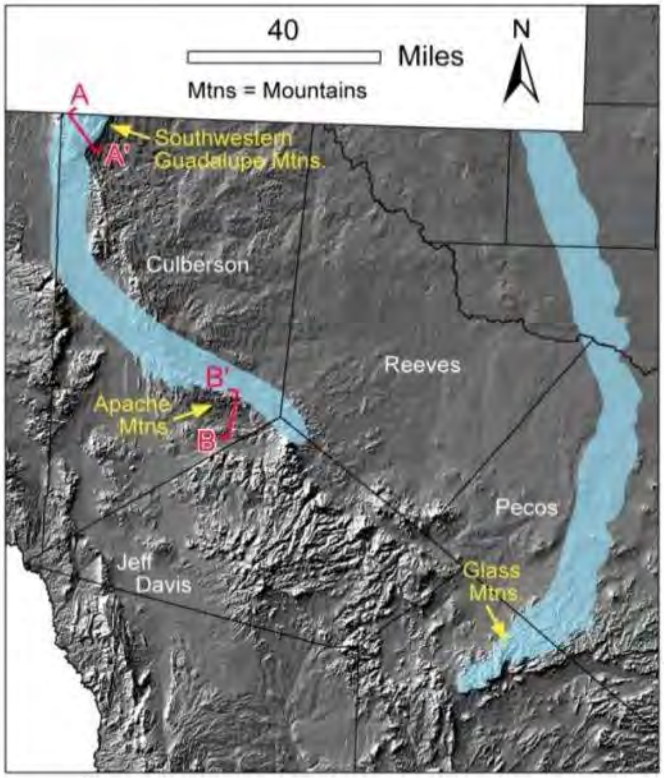


Figure 6-56. **Cross-section locations overlaying a digital elevation model. Aquifer is highlighted in blue (modified from King, 1948; Hays, 1964; Tyrrell, 1969; and Pray, 1988).**

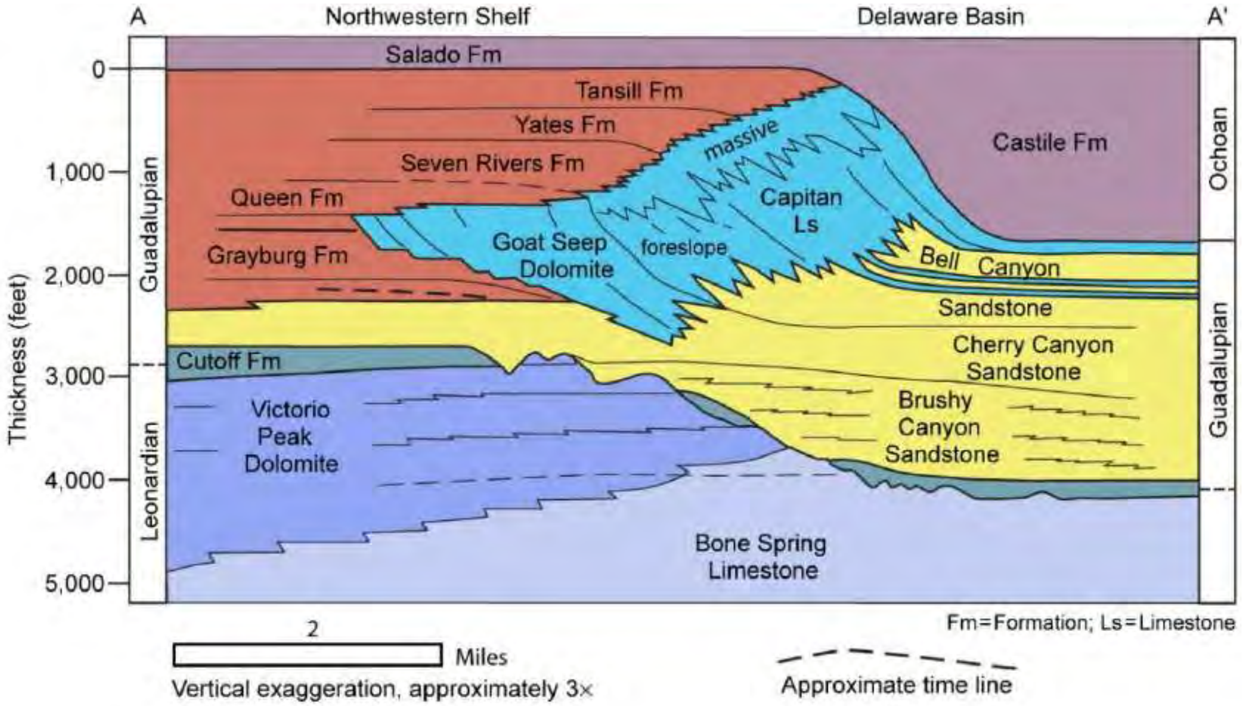
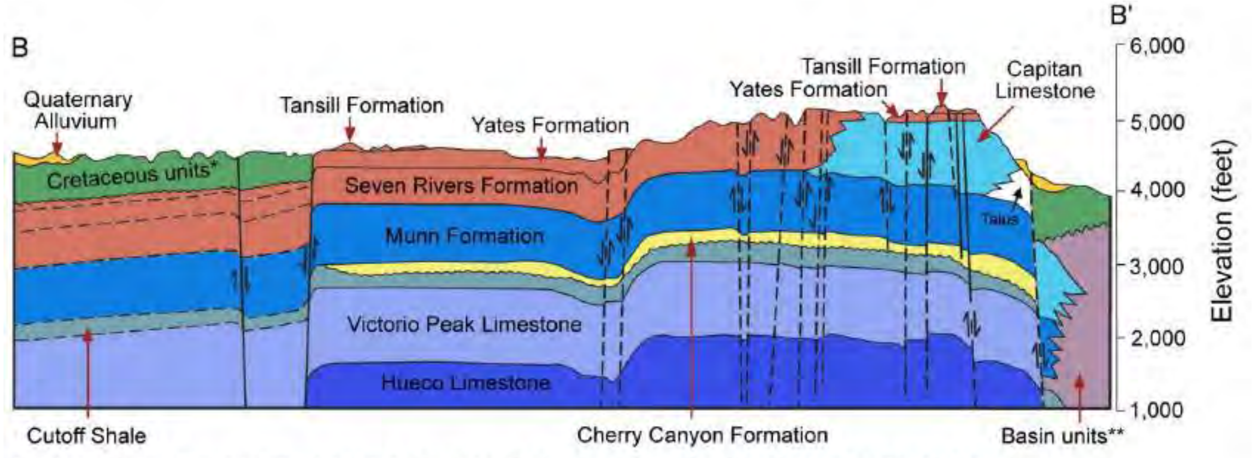


Figure 6-57. Stratigraphic cross-section of the Capitan Reef Complex Aquifer from A to A′, shown in Figure 6-56 (modified from King, 1948; Hays, 1964; Tyrrell, 1969; and Pray, 1988).



* includes Boracho Limestone (Levinson Member), Finlay Limestone, Cox Sandstone, Yearwood Formation
** includes Rustler Formation, Castile Limestone, Bell Canyon Sandstone, Cherry Canyon Sandstone

Figure 6-58. Stratigraphic cross-section of the Capitan Reef Complex Aquifer from B to B′, shown in Figure 6-56 (modified from Wood, 1965).

Flows to surface water and other aquifers

A portion of the Capitan Reef Complex Aquifer discharges to the Pecos River, and water from the Capitan Reef Complex Aquifer is thought to contribute to the baseflow of San Solomon Springs in Reeves County. A summary of baseflow in the outcrop areas of the Capitan Reef Complex Aquifer is reported in Table 6-38. The Capitan Reef Complex Aquifer is separated from the overlying Rustler and Dockum aquifers by the Salado and Castille Formations, which form an effective aquitard preventing groundwater flow. Groundwater availability model analysis does not estimate any inter-aquifer flow between the Capitan Reef Complex Aquifer and other major and minor aquifers.

Table 6-38. Summary of groundwater flow from the Capitan Reef Complex Aquifer to surface water.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Brewster	90	0.3	0.1
Culberson	66	0.5	0.2
Hudspeth	4	0	0
Pecos	27	0.1	0.1
Total	**187**	**1**	**0**

Water quantity

Total storage in the Capitan Reef Complex Aquifer is estimated to be more than 55 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 13.7 million to 41.3 million acre-feet (Table 6-39).

Table 6-39. Total estimated recoverable storage in the Capitan Reef Complex Aquifer, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Brewster	2,500,000	625,000	1,875,000
Culberson	21,000,000	5,250,000	15,750,000
Hudspeth	1,100,000	275,000	825,000
Jeff Davis	760,000	190,000	570,000
Pecos	16,800,000	4,200,000	12,600,000
Reeves	930,000	232,500	697,500
Ward	5,900,000	1,475,000	4,425,000
Winkler	6,100,000	1,525,000	4,575,000
Total	**55,090,000**	**13,772,500**	**41,317,500**

Water quality

Overall, the aquifer contains water of marginal quality, yielding small to large quantities of slightly saline to saline groundwater containing 1,000 to greater than 5,000 milligrams per liter of total dissolved solids. Water of the freshest quality, with total dissolved solids between 300 and 1,000 milligrams per liter, is present in the west near areas of recharge where the reef rock is exposed in several mountain ranges. Figure 6-59 shows total dissolved solids in the Capitan Reef Complex Aquifer.

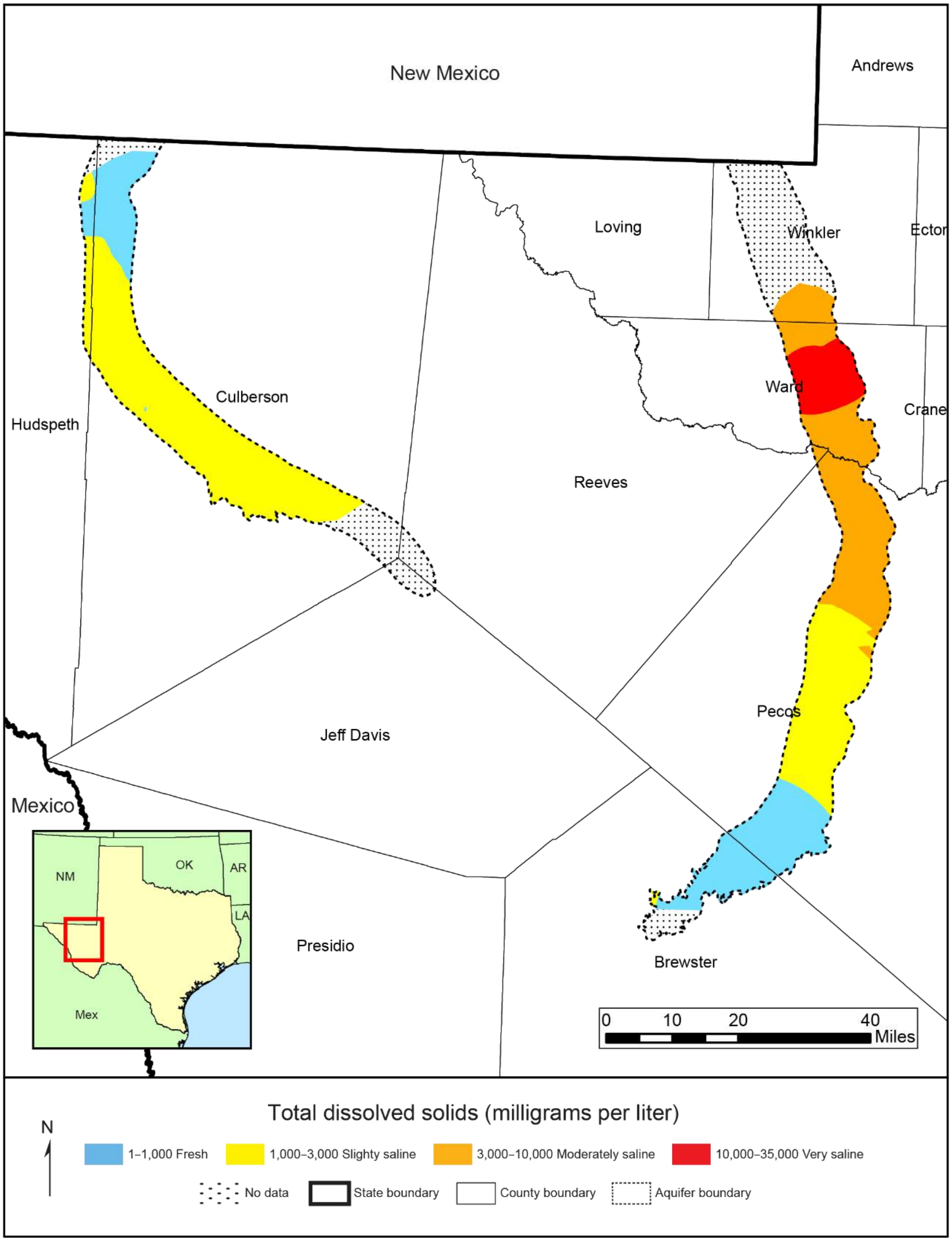


Figure 6-59. **Total dissolved solids in the Capitan Reef Complex Aquifer.**

6.15 Dockum Aquifer

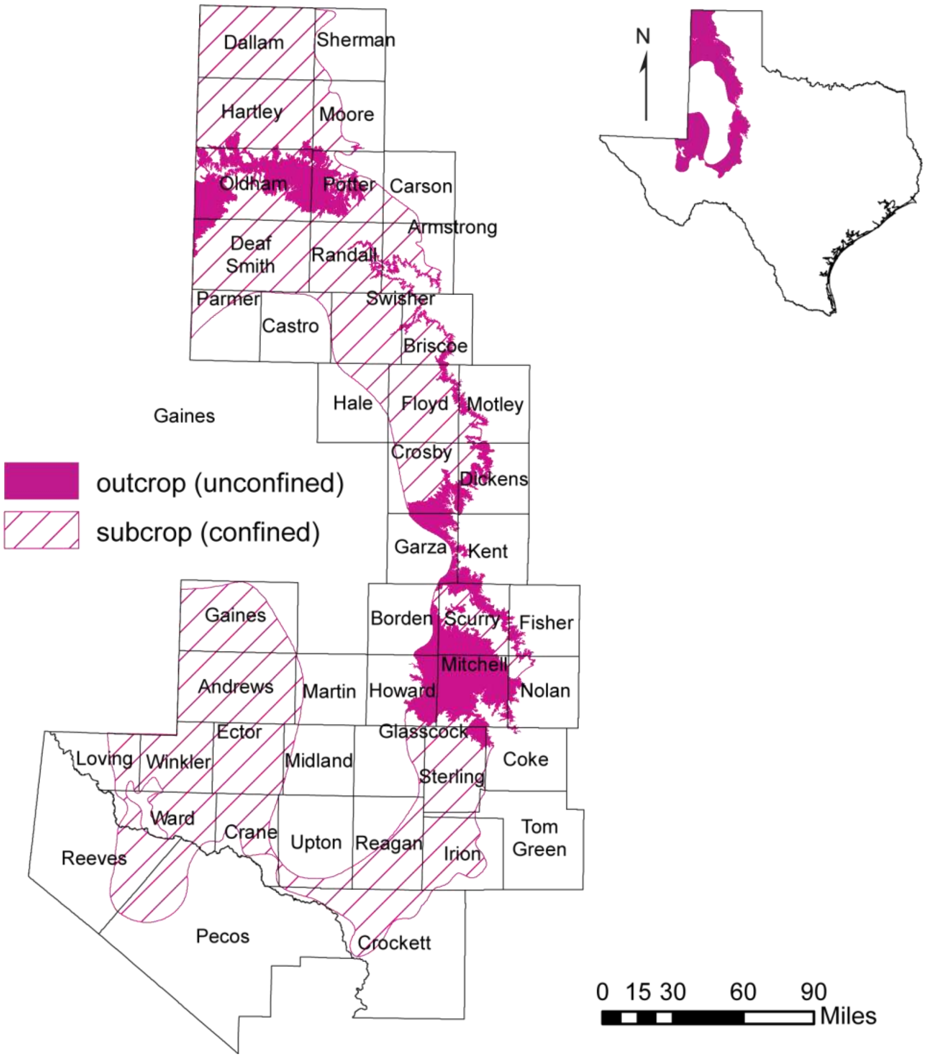


Figure 6-60. Extent of the Dockum Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 3,525 square miles
- Area in subsurface: 22,030 square miles
- Proportion of aquifer with groundwater conservation districts: 55 percent
- Number of counties containing the aquifer: 46

Geology and hydrogeology

The Dockum Aquifer is a minor aquifer found in the northwestern part of the state (Figure 6-60). It is defined stratigraphically by the Dockum Group, which is composed of sandstones, conglomerates, mudstones, and siltstones.

The Dockum Aquifer is overlain by the Ogallala Aquifer except in the outcrop areas along the Canadian and Colorado Rivers where the Ogallala has been eroded away, as shown in Figure 6-61. Permian red-bed shales underlie the Dockum Aquifer, forming a no-flow lower boundary. Portions of the Dockum Aquifer are in direct hydraulic communication with the Ogallala Aquifer, and it is treated as part of the High Plains Aquifer System for purposes of groundwater availability modeling (Deeds and others, 2015).

Groundwater in sandstone and conglomerate units is recoverable, with the highest yields typically coming from the coarsest grained deposits located at the base of the Dockum Group; these water-bearing sandstones are locally referred to as the Santa Rosa Aquifer. The mean hydraulic conductivity is 0.2 feet per day for the upper Dockum Aquifer and 0.4 feet per day for the lower Dockum Aquifer (Ewing and others, 2008) but can range as high as 22 feet per day in some areas (Deeds and others, 2015).

Recharge to the outcrop area of the Dockum Aquifer is believed to have increased over the last century from 0.15 inches per year to 0.58 inches per year as a result of development and accompanying land-use changes. Because the outcrop area is located downgradient from the confined portion of the aquifer, the recharge flows toward the Canadian or Colorado Rivers and their tributaries, with little or no recharge entering the confined area. The confined portions of the Dockum are believed to have been recharged by precipitation on higher elevation outcrops in New Mexico during the Pleistocene, which have since been eroded, cutting off recharge (Ewing and others, 2008).

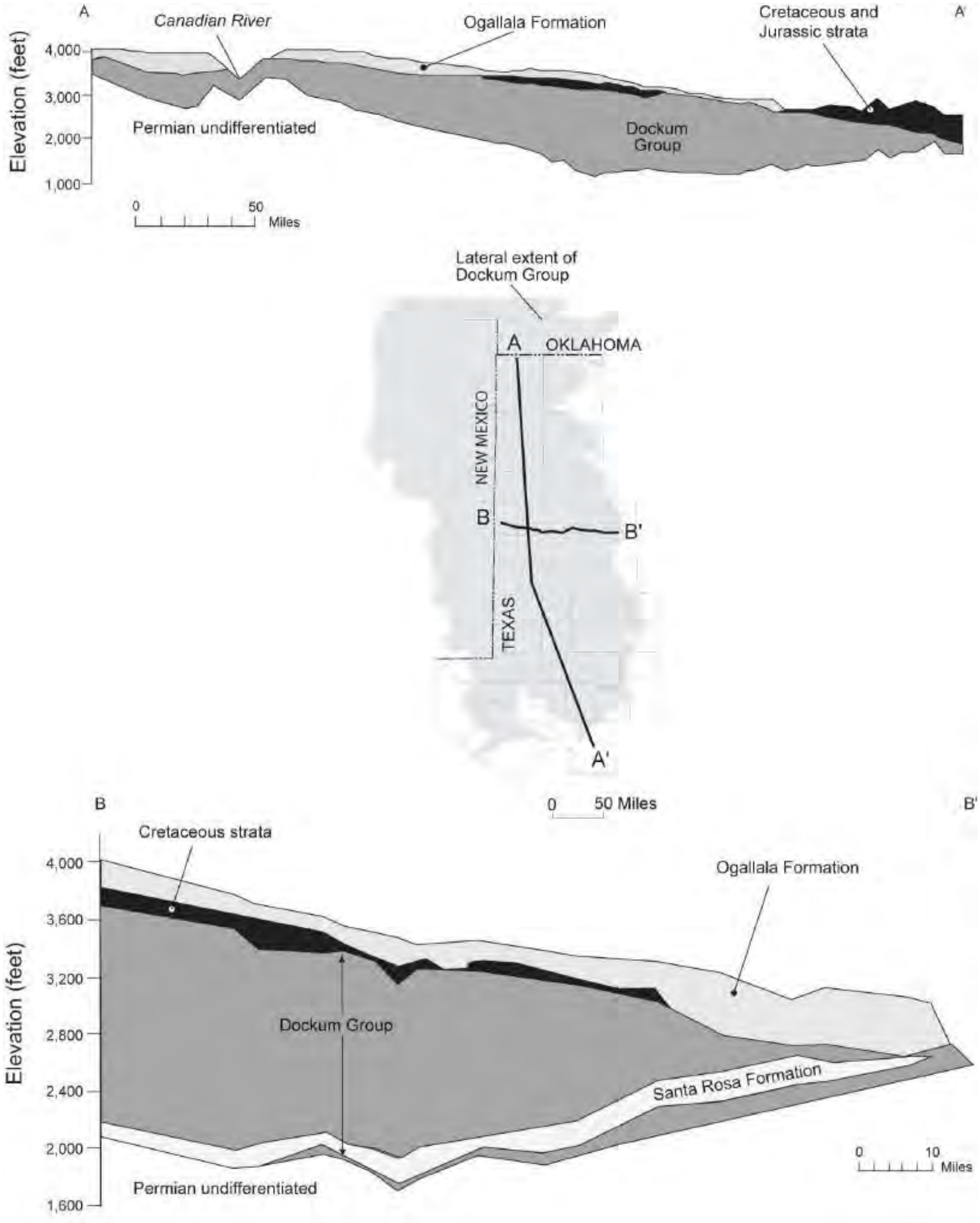


Figure 6-61. Structural cross-sections across the Dockum Aquifer (modifed from Bradley and Kalaswad, 2003).

Flows to surface water and other aquifers

Groundwater in the Dockum Aquifer generally flows to the southeast or east-southeast. Locally, groundwater diverts from this general direction toward springs and the Canadian, Brazos, and Colorado River drainage basins (Deeds and others, 2015). Springs occur in areas where Dockum Aquifer sediments intersect the water table. Brune (1981) described springs issuing from the Dockum Aquifer along the Pecos River Valley. Many of these springs are now dry or have lower flows than they did in the past (Bradley and Kalaswad, 2003).

Diffuse discharge from the Dockum Aquifer contributes to the baseflow of streams and rivers crossing its outcrop area. Analysis of U.S. Geological Survey baseflow index and hydrological landscape unit data give an estimated average surface discharge from the Dockum Aquifer of 18.2 cubic feet per second and a median discharge of 5.6 cubic feet per second. Table 6-40 shows a summary of baseflow in the outcrop areas of the Dockum Aquifer.

In some areas the water level in the Dockum Aquifer is higher than that in the Ogallala Aquifer, creating the potential for upward flow; chemical and isotopic data also support localized upward flow from the Dockum Group to the Ogallala Aquifer (Deeds and others, 2015). Table 6-41 shows groundwater availability model estimates of total flow and average annual flow between the Dockum Aquifer and other aquifers. Because of the large regional extent of the aquifer, some flow is estimated both from the Dockum Aquifer to the Ogallala Aquifer and from the Ogallala Aquifer to the Dockum Aquifer.

Table 6-40. Summary of groundwater flow from the Dockum Aquifer to surface water, by county

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Armstrong	52	0.1	0.1
Borden	91	0.3	0
Briscoe	58	0.2	0.1
Coke	14	0	0
Crosby	158	0.9	0.8
Deaf Smith	57	0.7	0.2
Dickens	144	1.1	0.6
Fisher	47	0.3	0
Floyd	36	0.3	0.2
Garza	206	0.4	0.1

Table 6-40 (continued). Summary of groundwater flow from the Dockum Aquifer to surface water, by county

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Hartley	38	0.1	0.1
Howard	250	1.1	0.2
Kent	72	0.4	0
Martin	25	0.1	0
Mitchell	725	3.4	0.2
Moore	7	0	0
Motley	53	0.6	0.4
Nolan	59	0.3	0
Oldham	735	4.8	1.8
Potter	294	1.3	0.4
Randall	22	0	0
Scurry	360	1.8	0.1
Sterling	46	0.1	0
Swisher	1	0	0
Total	**3,550**	**18**	**5**

Table 6-41. Model estimates of inter-aquifer flows between the Dockum Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Dockum Aquifer	Edwards-Trinity (Plateau) Aquifer	37,509
Dockum Aquifer	Ogallala Aquifer	2,241
Dockum Aquifer	Rita Blanca Aquifer	115
Edwards-Trinity (Plateau) Aquifer	Dockum Aquifer	2,948
Ogallala Aquifer	Dockum Aquifer	27,497
Rita Blanca Aquifer	Dockum Aquifer	83
Rustler Aquifer	Dockum Aquifer	1

Water quantity

Total storage in the Dockum Aquifer is estimated to be over 1.5 billion acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 373.5 million to 1.1 billion acre-feet (Table 6-42).

Table 6-42. Total estimated recoverable storage in the Dockum Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Andrews	220,000,000	55,000,000	165,000,000
Armstrong	7,000,000	1,750,000	5,250,000
Borden	7,600,000	1,900,000	5,700,000
Briscoe	18,000,000	4,500,000	13,500,000
Carson	1,900,000	475,000	1,425,000
Castro	7,000,000	1,750,000	5,250,000
Coke	520,000	130,000	390,000
Crane	30,000,000	7,500,000	22,500,000
Crockett	14,000,000	3,500,000	10,500,000
Crosby	30,000,000	7,500,000	22,500,000
Dallam	80,000,000	20,000,000	60,000,000
Deaf Smith	130,000,000	32,500,000	97,500,000
Dickens	3,400,000	850,000	2,550,000
Ector	100,000,000	25,000,000	75,000,000
Fisher	1,300,000	325,000	975,000
Floyd	40,000,000	10,000,000	30,000,000
Gaines	200,000,000	50,000,000	150,000,000
Garza	4,900,000	1,225,000	3,675,000
Glasscock	11,000,000	2,750,000	8,250,000
Hale	16,000,000	4,000,000	12,000,000
Hartley	96,000,000	24,000,000	72,000,000
Howard	22,000,000	5,500,000	16,500,000
Irion	9,100,000	2,275,000	6,825,000
Kent	1,400,000	350,000	1,050,000
Loving	4,500,000	1,125,000	3,375,000
Martin	11,000,000	2,750,000	8,250,000
Midland	10,000,000	2,500,000	7,500,000
Mitchell	27,000,000	6,750,000	20,250,000
Moore	7,400,000	1,850,000	5,550,000
Motley	1,800,000	450,000	1,350,000

Table 6-42 (continued). Total estimated recoverable storage in the Dockum Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Nolan	2,100,000	525,000	1,575,000
Oldham	43,000,000	10,750,000	32,250,000
Parmer	30,000,000	7,500,000	22,500,000
Pecos	19,500,000	4,875,000	14,625,000
Potter	10,000,000	2,500,000	7,500,000
Randall	46,000,000	11,500,000	34,500,000
Reagan	17,000,000	4,250,000	12,750,000
Reeves	12,000,000	3,000,000	9,000,000
Scurry	32,000,000	8,000,000	24,000,000
Sherman	540,000	135,000	405,000
Sterling	33,000,000	8,250,000	24,750,000
Swisher	66,000,000	16,500,000	49,500,000
Tom Green	1,100,000	275,000	825,000
Upton	9,300,000	2,325,000	6,975,000
Ward	18,000,000	4,500,000	13,500,000
Winkler	42,000,000	10,500,000	31,500,000
Total	**1,494,360,000**	**373,590,000**	**1,120,770,000**

Water quality

Water quality in the Dockum Aquifer is generally poor and very hard, with freshwater in outcrop areas in the east and brine in the western subsurface portions of the aquifer. The distribution of total dissolved solids in the Dockum Aquifer, based on data from over 1,000 wells completed in the aquifer, is shown in Figure 6-62.

Naturally occurring radioactivity from uranium present within the aquifer has resulted in gross alpha radiation in excess of the state’s primary drinking water standard in about 25 percent of Dockum Aquifer wells. Radium-226 and -228 also occur in amounts above acceptable standards. Nitrate is present at concentrations exceeding primary drinking water standards in about 10 percent of the wells, mostly in the outcrop areas, where it is associated with agricultural operations. Dockum Aquifer groundwater exceeds secondary drinking water standards for chloride, fluoride, iron, sulfate, and total dissolved solids in about one-third of the wells tested, primarily as a result of the evaporite minerals present in the Dockum Group and underlying formations of the Permian Basin (Reedy and others, 2011).

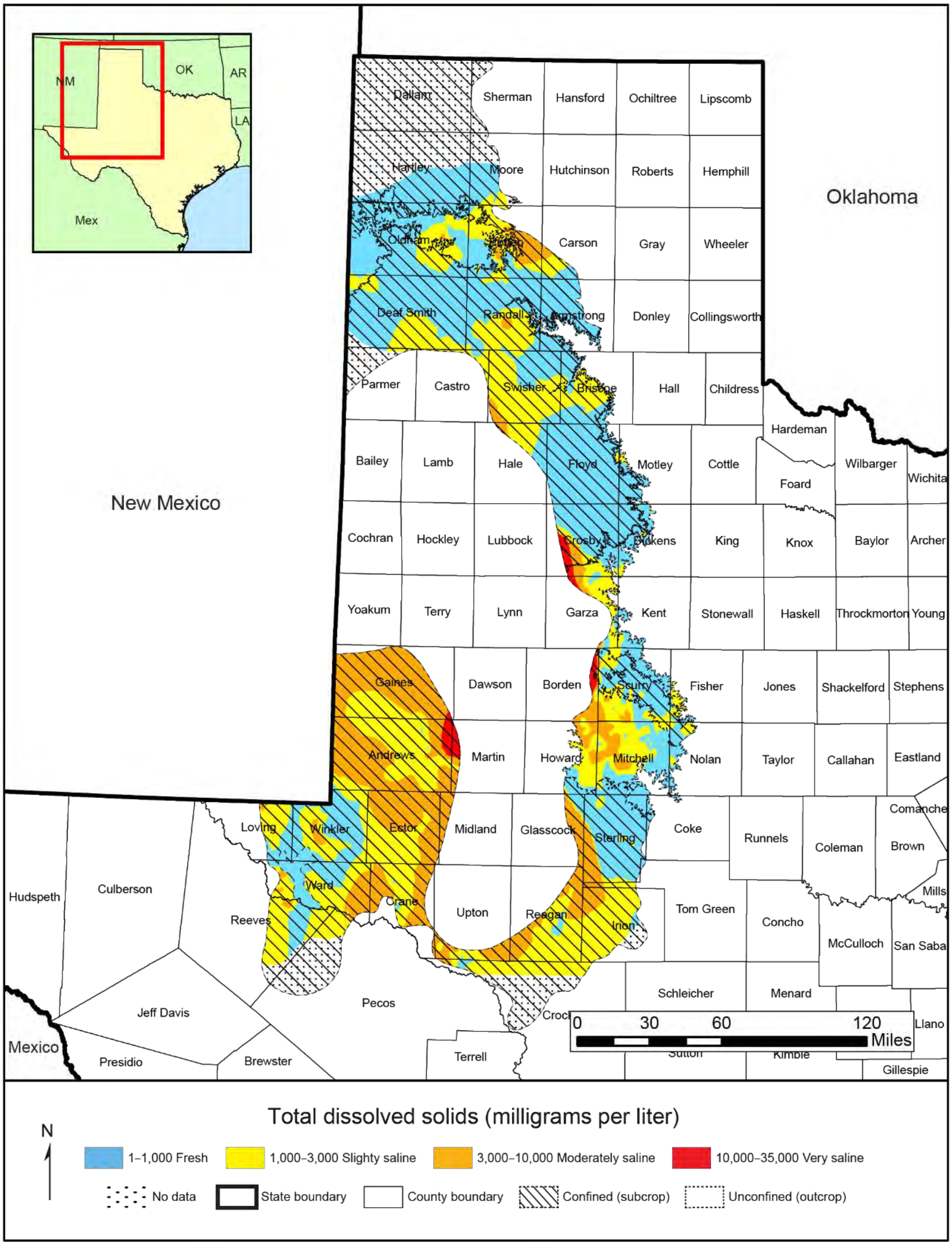


Figure 6-62. Total dissolved solids in the Dockum Aquifer.

6.16 Edwards-Trinity (High Plains) Aquifer

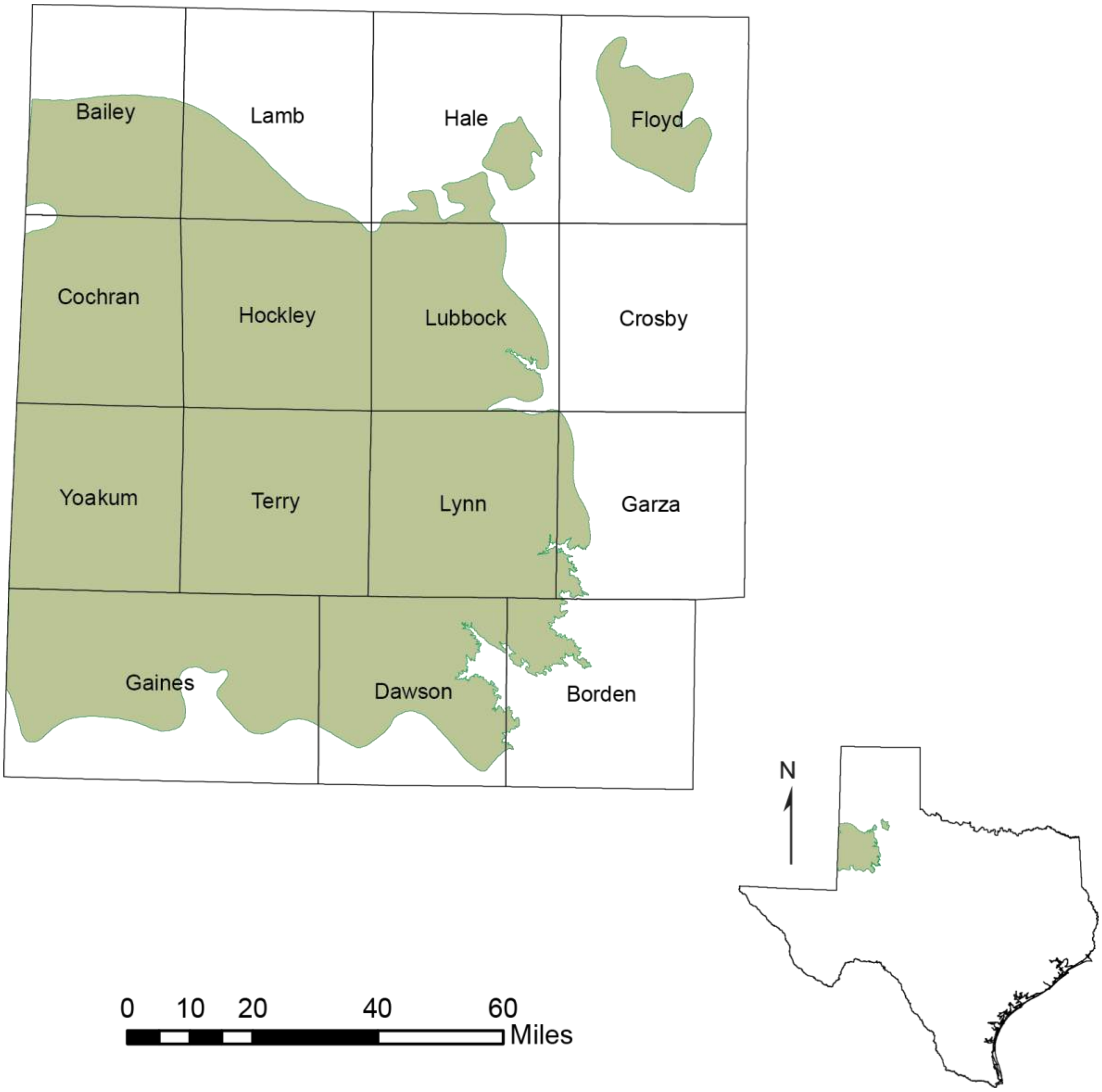


Figure 6-63. Extent of the Edwards-Trinity High Plains Aquifer.

Aquifer characteristics

- Aquifer type: mostly confined
- Area of aquifer: 7,912 square miles
- Proportion of aquifer with groundwater conservation districts: 98 percent
- Number of counties containing the aquifer: 15

Geology and hydrogeology

The Edwards-Trinity (High Plains) Aquifer is a minor aquifer that underlies about 9,000 square miles of the Ogallala Aquifer in western Texas and eastern New Mexico (Figure 6-63). Its water-producing units include sandstone and limestone. Freshwater saturated thickness in the aquifer averages 126 feet. Regional groundwater flow in the aquifer is to the southeast, but locally, flow is determined by the presence of paleo-channels containing Ogallala Formation sediments that are incised into the Cretaceous limestone forming the Edwards-Trinity (High Plains) Aquifer. Recharge to the aquifer is primarily due to downward leakage from the younger Ogallala Aquifer. The greatest amounts of recharge most likely occur where low-permeability clay layers, which lie between the Edwards-Trinity (High Plains) and Ogallala aquifers, are missing, thin, or relatively permeable (Figure 6-64). Groundwater in the Edwards-Trinity (High Plains) Aquifer generally is confined, although there are small areas where the aquifer is unconfined. Blandford and others (2008) modeled the specific storage of the confined portion of the aquifer with a value of 3×10^{-6} based on results for similar aquifers.

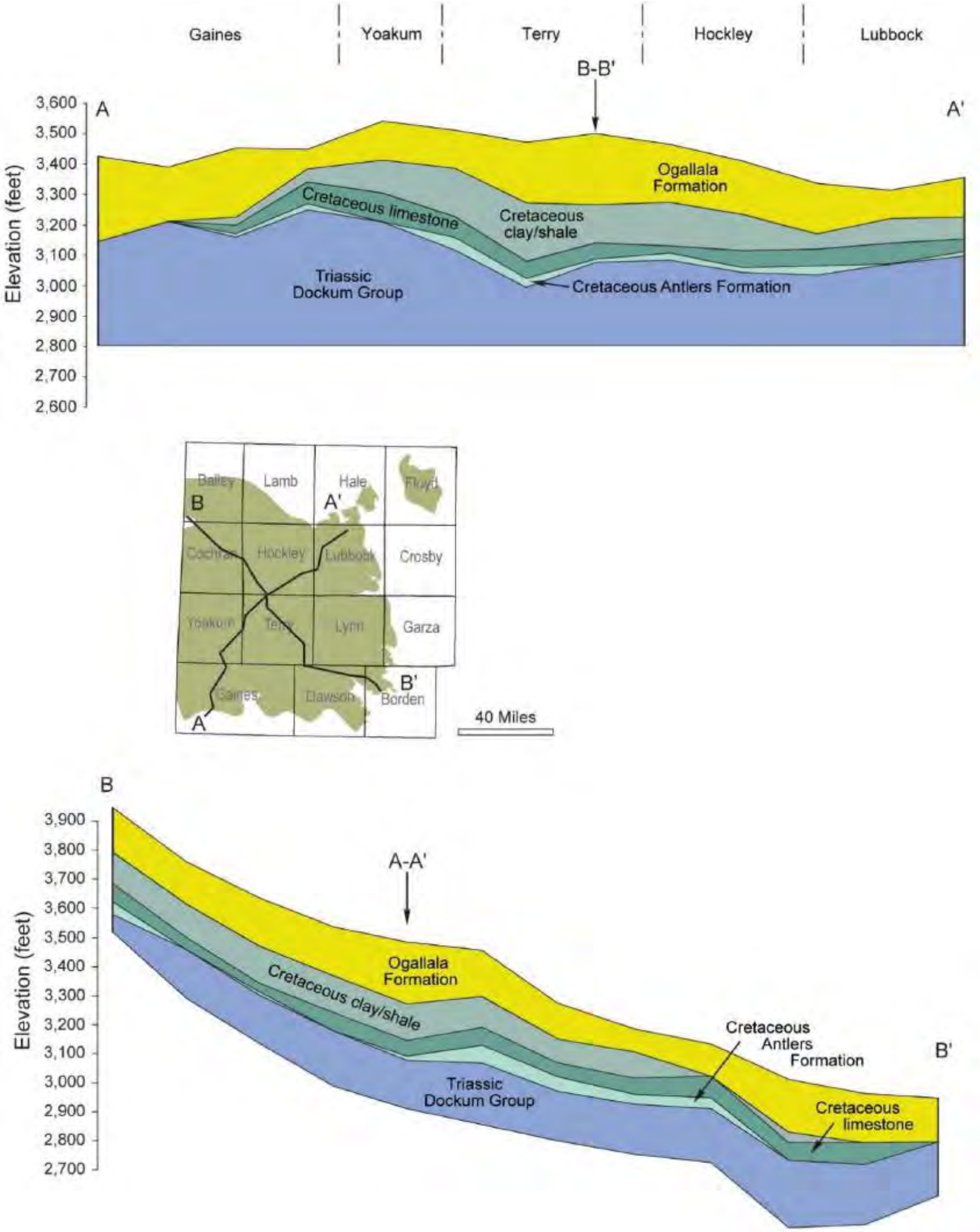


Figure 6-64. **Geologic cross-section across the Edwards-Trinity (High Plains) Aquifer (modified from Blandford and others, 2008).**

Flows to surface water and other aquifers

Table 6-43 shows a summary of baseflow in the Edwards-Trinity (High Plains) Aquifer. Discharge from the Edwards-Trinity (High Plains) Aquifer occurs at springs and seeps along the eastern caprock escarpment and at a number of large salt lakes west of the escarpment (Blandford and others, 2008). Table 6-44 shows groundwater availability model estimates of total flow and average annual flow between the Edwards-Trinity (High Plains) Aquifer and other aquifers. The predominant direction of flow is downward from the Ogallala Aquifer into the Edwards-Trinity (High Plains) Aquifer, although in some areas there is upward leakage to the Ogallala Aquifer as a result of water table drawdown in that aquifer.

Table 6-43. Summary of groundwater flow from the Edwards-Trinity (High Plains) Aquifer to surface water.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Borden	17	0.1	0
Dawson	14	0	0.1
Garza	3	0	0
Lynn	2	0	0
Total	**36**	**0.1**	**0.1**

Table 6-44. Model estimates of inter-aquifer flows between the Edwards-Trinity (High Plains) Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Edwards-Trinity (High Plains) Aquifer	Ogallala Aquifer	5,544
Ogallala Aquifer	Edwards-Trinity (High Plains) Aquifer	13,812

Water quantity

Total storage in the Edwards-Trinity (High Plains) Aquifer is estimated to be more than 23 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, or about 5.9 million to 17.7 billion acre-feet (Table 6-45).

Table 6-45. Total estimated recoverable storage in the Edwards-Trinity (High Plains) Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Bailey	690,000	172,500	517,500
Borden	1,600,000	400,000	1,200,000
Cochran	1,700,000	425,000	1,275,000
Dawson	1,000,000	250,000	750,000
Floyd	730,000	182,500	547,500
Gaines	3,100,000	775,000	2,325,000
Garza	120,000	30,000	90,000
Hale	870,000	217,500	652,500
Hockley	2,200,000	550,000	1,650,000
Lamb	500,000	125,000	375,000
Lubbock	2,000,000	500,000	1,500,000
Lynn	3,400,000	850,000	2,550,000
Terry	3,300,000	825,000	2,475,000
Yoakum	2,500,000	625,000	1,875,000
Total	**23,710,000**	**5,927,500**	**17,782,500**

Water quality

Groundwater in the Edwards-Trinity (High Plains) Aquifer typically contains more total dissolved solids than does the overlying Ogallala Aquifer. It generally is slightly saline, with total dissolved solids ranging from 1,000 to 2,000 milligrams per liter, but can range from 400 to more than 3,000 milligrams per liter. Areas with higher total dissolved solids concentrations are primarily located in the south central region of the aquifer (Figure 6-65). Groundwater is poorest in quality where the aquifer is overlain by saline lakes or the gypsum-rich Tahoka and Double Lakes formations. The eastern portion of the aquifer is at a high risk of exceeding maximum contaminant levels for arsenic, fluoride, and nitrate-N (Reedy and others, 2011).

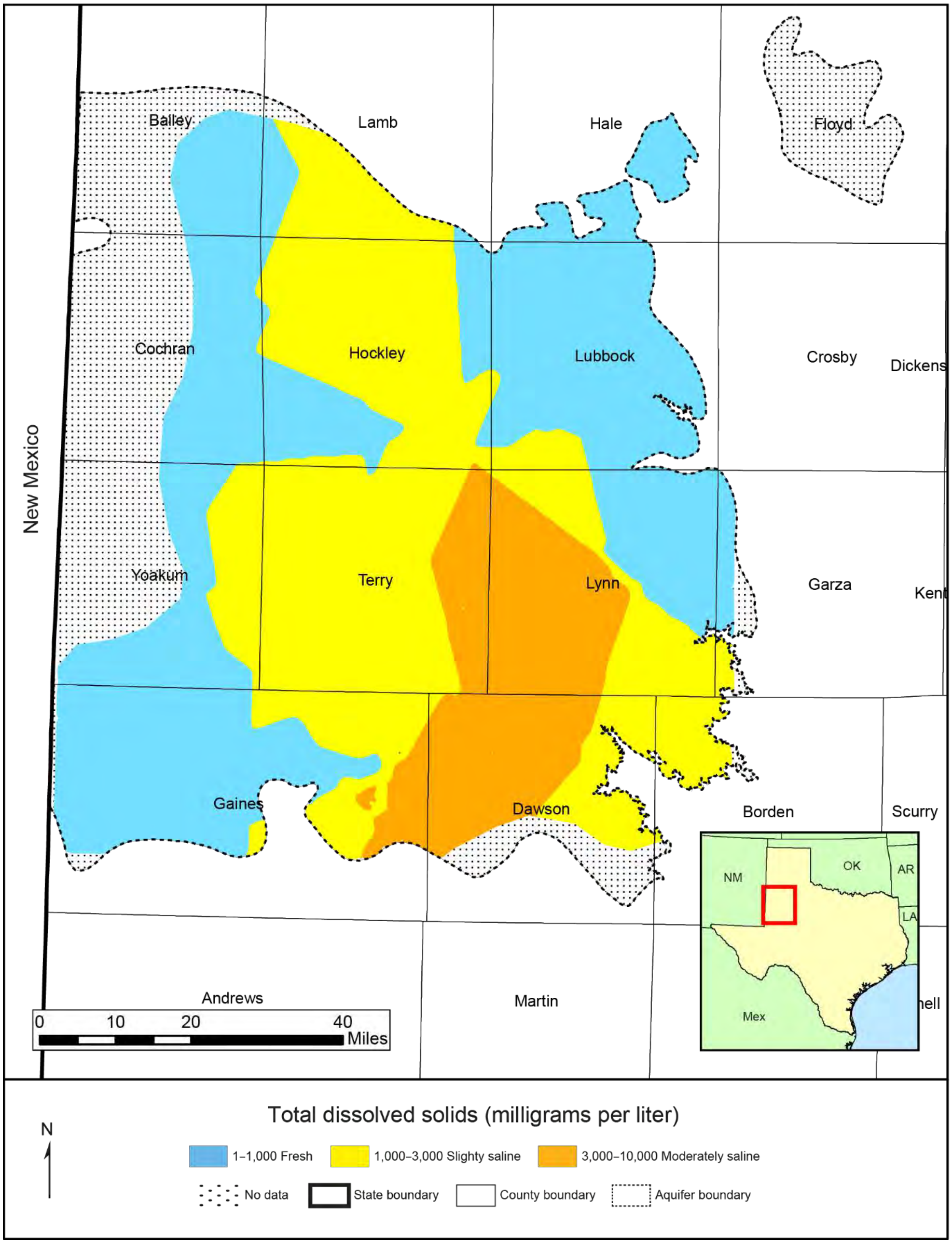


Figure 6-65. Total dissolved solids in the Edwards-Trinity (High Plains) Aquifer.

6.17 Ellenburger-San Saba Aquifer

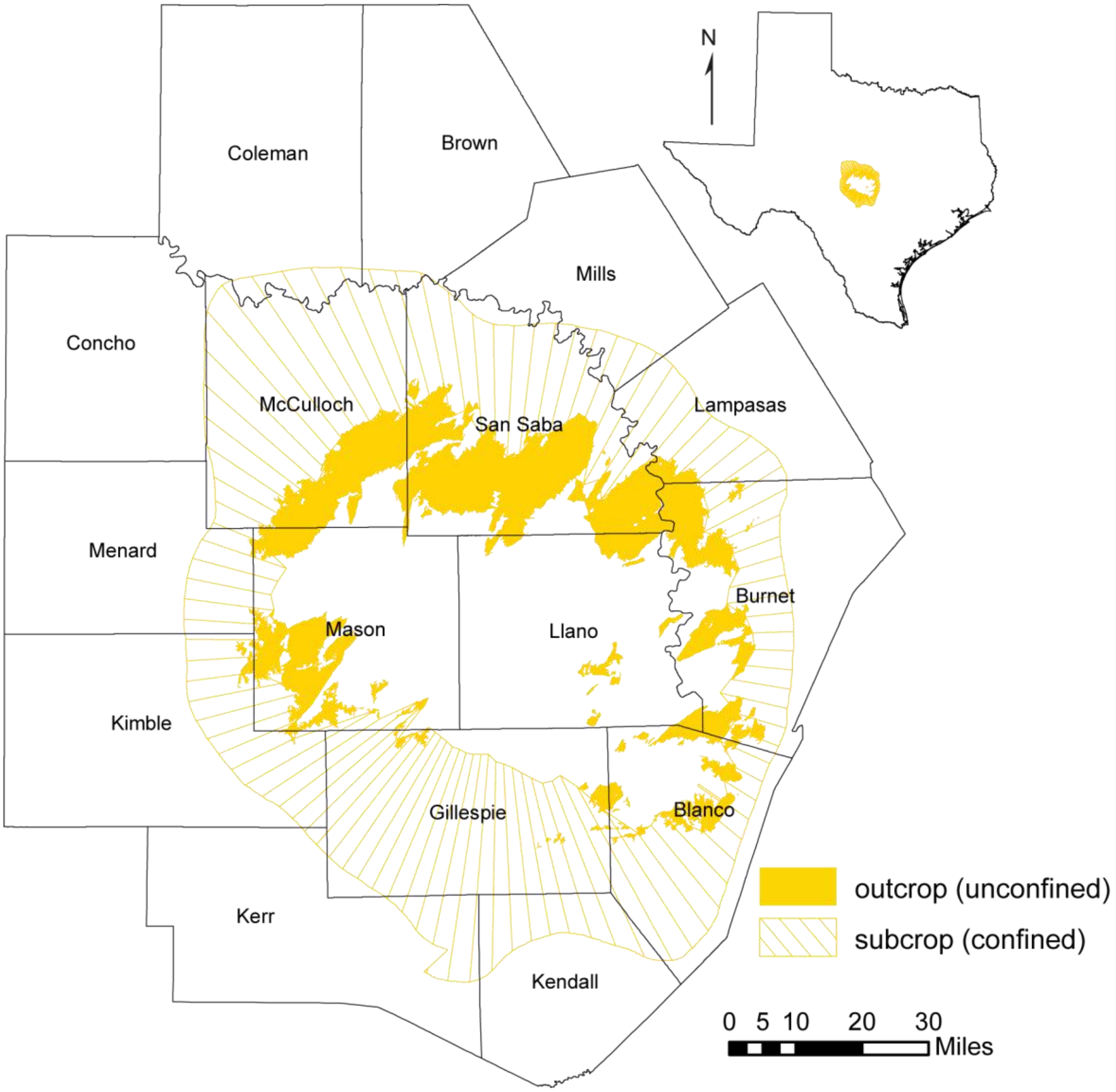


Figure 6-66. Extent of the Ellenburger-San Saba Aquifer.

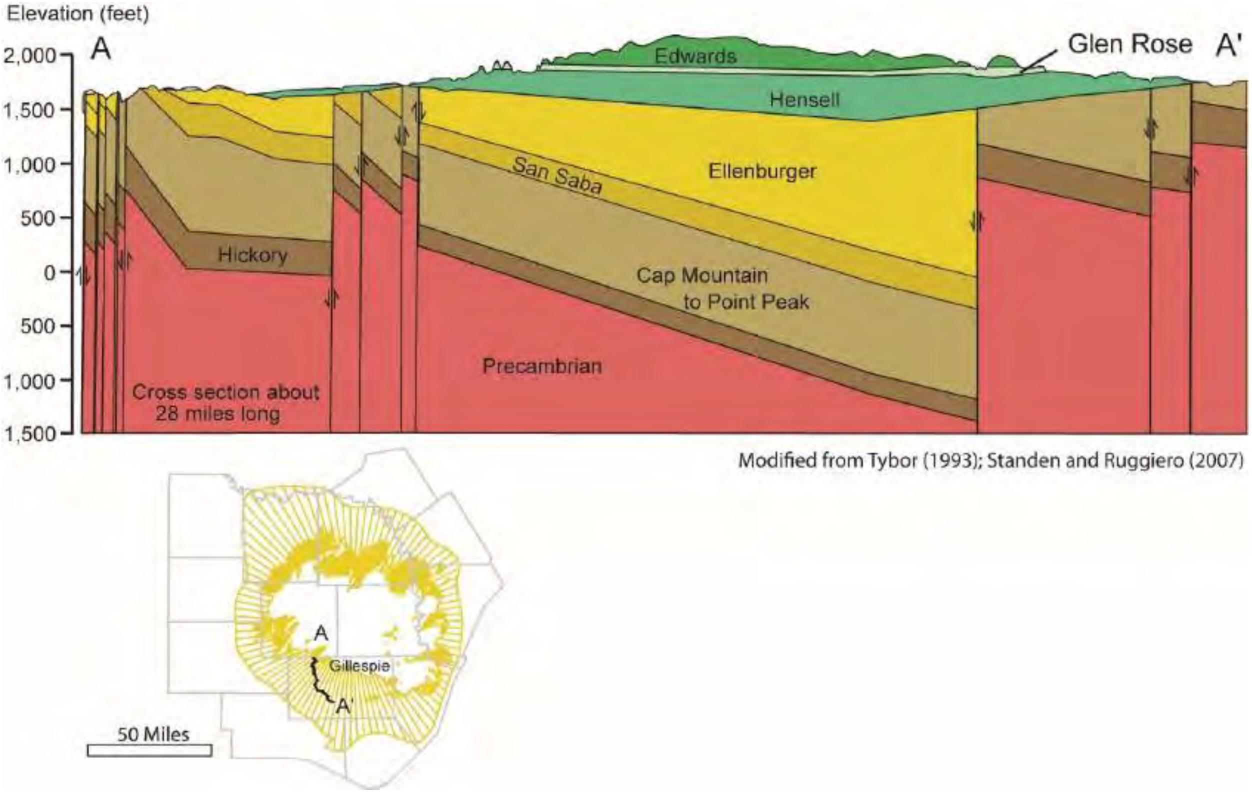
Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 1,152 square miles
- Area in subsurface: 4,279 square miles
- Proportion of aquifer with groundwater conservation districts: 80 percent
- Number of counties containing the aquifer: 16

Geology and hydrogeology

The Ellenburger-San Saba Aquifer is a minor aquifer that is found in parts of 16 counties in the Llano Uplift area of Central Texas (Figure 6-66). The aquifer consists of a sequence of limestone and dolomite formations that crop out in a circular pattern around the uplift and dip radially into the subsurface to depths of approximately 3,000 feet (Figure 6-67). Regional block faulting has significantly compartmentalized the aquifer. The maximum thickness of the aquifer is about 2,700 feet.

Water occurs in fractures, cavities, and solution channels and is commonly under confined conditions. The aquifer is highly permeable in places, as indicated by wells that yield as much as 1,000 gallons per minute. Numerous springs issue from the aquifer, maintaining the baseflow of streams in the area.



Modified from Tybor (1993); Standen and Ruggiero (2007)

Figure 6-67. Structural cross-section across the Ellenburger-San Saba Aquifer (modified from Tybor, 1993; Standen and Ruggiero, 2007).

Flows to surface water and other aquifers

Precipitation and runoff contribute recharge to the Ellenburger-San Saba Aquifer in upland areas, with discharge occurring as stream baseflow at lower elevations. Faulting around the Llano Uplift and dissolution features in carbonate formations produce locally complex groundwater and surface-water interactions. Table 6-46 shows a summary of baseflow in the outcrop areas of the Ellenburger-San Saba Aquifer. Table 6-47 shows groundwater availability model estimates of total flow and average annual flow between the Ellenburger-San Saba Aquifer and other aquifers. Because of local differences in topography and structural off-sets along faults, flows may occur in both directions between aquifers.

Table 6-46. Summary of groundwater flow from the Ellenburger-San Saba Aquifer to surface water.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Blanco	36	2	0.5
Burnet	168	9.3	1.8
Gillespie	13	0.7	0.2
Kimble	7	0.4	0.2
Lampasas	17	0.9	0.2
Llano	62	2.8	0.9
Mason	182	7.3	2.8
McCulloch	172	3.1	0.9
Menard	1	0	0
San Saba	436	13.6	3
Total	**1,094**	**40**	**11**

Table 6-47. Model estimates of inter-aquifer flows between the Ellenburger-San Saba Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Ellenburger-San Saba Aquifer	Hickory Aquifer	9,305
Ellenburger-San Saba Aquifer	Marble Falls Aquifer	2,368
Edwards-Trinity (Plateau) Aquifer	Ellenburger-San Saba Aquifer	929
Hickory Aquifer	Ellenburger-San Saba Aquifer	21,654
Marble Falls Aquifer	Ellenburger-San Saba Aquifer	3,647
Trinity Aquifer	Ellenburger-San Saba Aquifer	1,285

Water quantity

Total storage in the Ellenburger-San Saba Aquifer is estimated to be more than 87 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 21.7 million to 65.2 million acre-feet (Table 6-48).

Table 6-48. Total estimated recoverable storage in the Ellenburger-San Saba Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Blanco	8,300,000	2,075,000	6,225,000
Brown	420,000	105,000	315,000
Burnet	8,100,000	2,025,000	6,075,000
Coleman	1,400,000	350,000	1,050,000
Concho	62,000	15,500	46,500
Gillespie	6,500,000	1,625,000	4,875,000
Kendall	3,500,000	875,000	2,625,000
Kerr	2,100,000	525,000	1,575,000
Kimble	6,000,000	1,500,000	4,500,000
Lampasas	8,500,000	2,125,000	6,375,000
Llano	350,000	87,500	262,500

Table 6-48 (continued). Total estimated recoverable storage in the Ellenburger-San Saba Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Mason	1,900,000	475,000	1,425,000
McCulloch	16,000,000	4,000,000	12,000,000
Menard	1,600,000	400,000	1,200,000
Mills	2,300,000	575,000	1,725,000
San Saba	20,000,000	5,000,000	15,000,000
Total	**87,032,000**	**21,758,000**	**65,274,000**

Water quality

Groundwater in the Ellenburger-San Saba Aquifer is generally very good and usually has less than 1,000 milligrams per liter of total dissolved solids (Figure 6-68). Total dissolved solids increase down-dip and radially outward from the Llano Uplift, centered in Llano County. Elevated concentrations of radionuclides also occur in the aquifer, mostly in the northern part of the aquifer (Reedy and others, 2011).

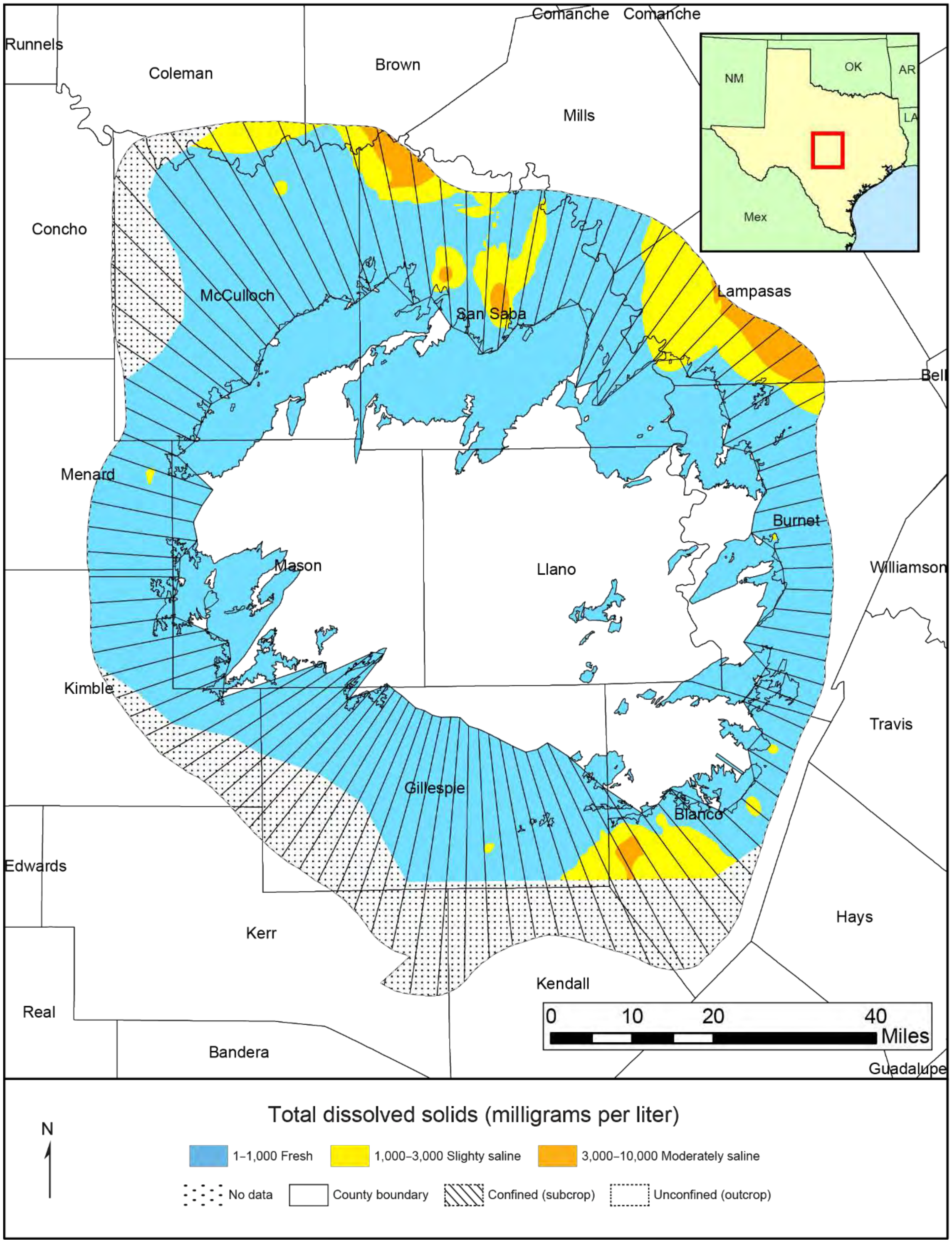


Figure 6-68. **Total dissolved solids in the Ellenburger-San Saba Aquifer.**

6.18 Hickory Aquifer

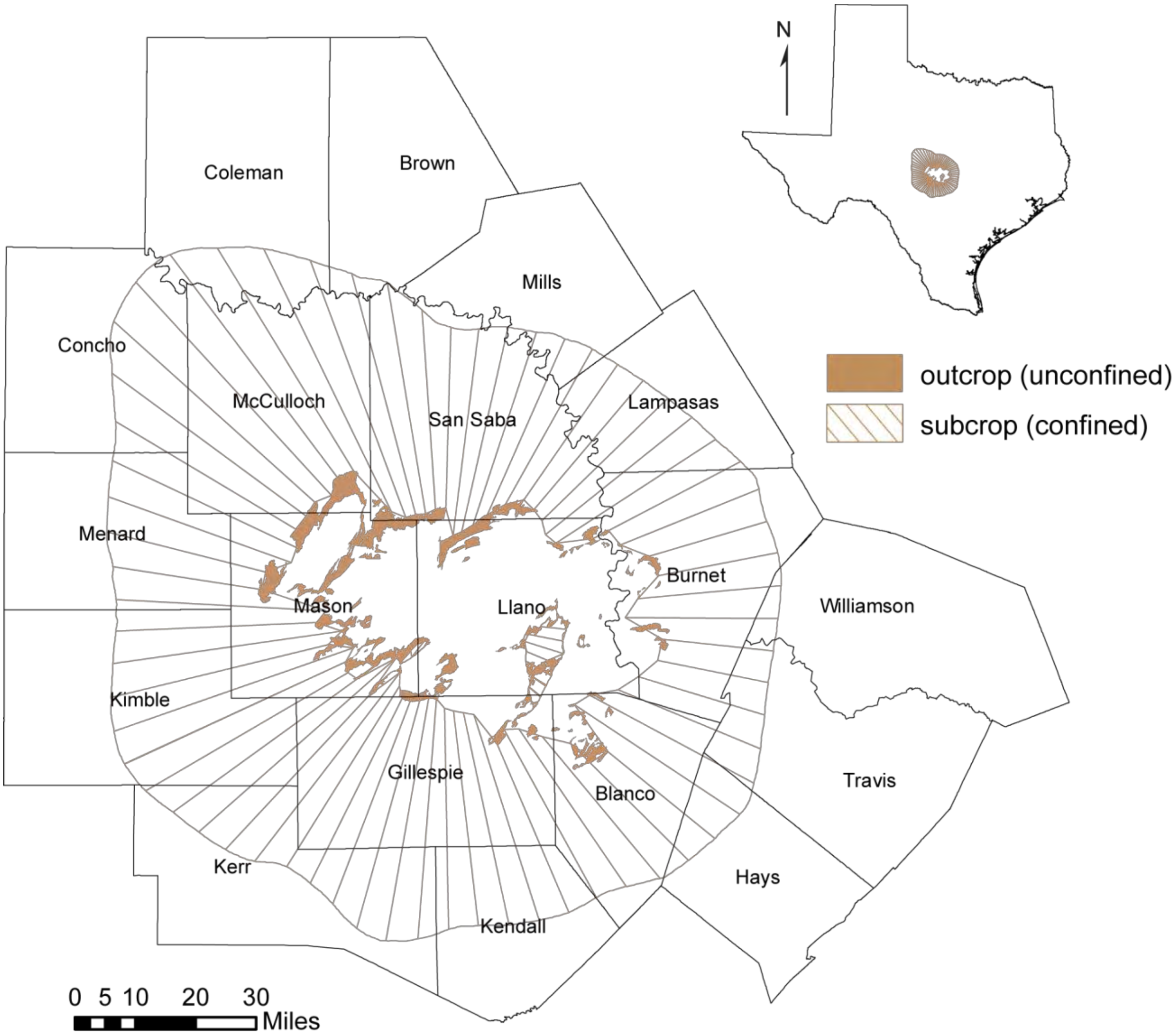


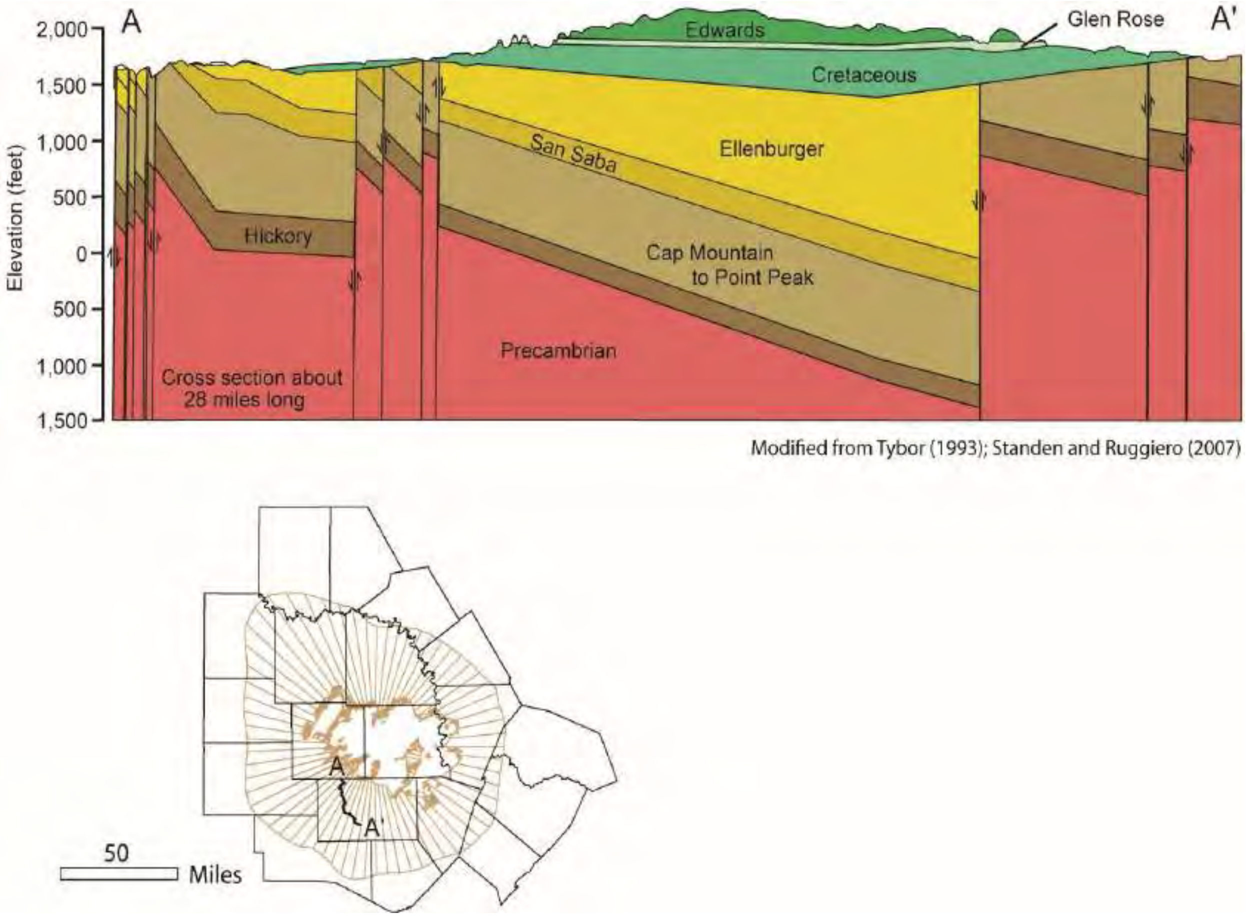
Figure 6-69. Extent of the Hickory Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 272 square miles
- Area in subsurface: 8,317 square miles
- Proportion of aquifer with groundwater conservation districts: 83 percent
- Number of counties containing the aquifer: 19

Geology and hydrogeology

The Hickory Aquifer is a minor aquifer in the central part of the state that consists of the water-bearing parts of the Hickory Sandstone Member (Figure 6-69). The Hickory Member is a mixture of terrestrial and marine sandstones, siltstones, and mudstones. It is divided into three units with quartz sand in the lower unit, silty or argillaceous sand in the middle unit, and hematite-cemented sand in the upper unit (Shi and others, 2016b). In general, the Hickory Member thickens from north to south, with zero thickness at the Precambrian granite knobs of the Llano Uplift to about 1,000 feet in Kerr County to the south (Figure 6-70). The top and base of the Hickory Member are strong geophysical log correlation surfaces (Standen and Ruggiero, 2007) with relatively high gamma readings. The freshwater saturated thickness of the Hickory Aquifer averages about 350 feet.



Modified from Tybor (1993); Standen and Ruggiero (2007)

Figure 6-70. **Structural cross-section across the Hickory Aquifer (modified from Tybor, 1993; Standen and Guggiero, 2007).**

Flows to surface water and other aquifers

Inflow to the Hickory Aquifer occurs as cross-formational flow from younger units and recharge by precipitation in the outcrop area. Outflow includes groundwater pumping, leakage to surface-water bodies, and cross-formational flow to the Ellenburger-San Saba Aquifer (Shi and others, 2016a). Table 6-49 summarizes baseflow in the outcrop areas of the Hickory Aquifer by county. Table 6-50 shows groundwater availability model estimates of total flow and average annual flow between the Hickory Aquifer and other aquifers.

Table 6-49. Summary of groundwater flow from the Hickory Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Blanco	18	1	0.2
Burnet	13	0.7	0.1
Gillespie	12	0.6	0.2
Llano	62	2.6	0.9
Mason	117	4.6	1.7
McCulloch	22	0.5	0.2
San Saba	25	0.9	0.3
Total	**269**	**11**	**4**

Table 6-50. Model estimates of inter-aquifer flows between the Hickory Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Hickory Aquifer	Ellenburger-San Saba Aquifer	21,654
Hickory Aquifer	Trinity Aquifer	64
Edwards-Trinity (Plateau) Aquifer	Hickory Aquifer	43
Ellenburger-San Saba Aquifer	Hickory Aquifer	9,305

Water quantity

Total storage in the Hickory Aquifer is estimated to be more than 66 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 16.5 million to 49.6 million acre-feet (Table 6-51).

Table 6-51. Total estimated recoverable storage in the Hickory Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Blanco	4,700,000	1,175,000	3,525,000
Brown	220,000	55,000	165,000
Burnet	6,600,000	1,650,000	4,950,000
Coleman	1,500,000	375,000	1,125,000
Concho	2,800,000	700,000	2,100,000
Gillespie	7,200,000	1,800,000	5,400,000
Kimble	5,900,000	1,475,000	4,425,000
Lampasas	2,800,000	700,000	2,100,000
Llano	1,000,000	250,000	750,000
Mason	5,400,000	1,350,000	4,050,000
McCulloch	8,500,00	2,125,000	3,375,000
Menard	4,500,000	1,125,000	3,375,000
Mills	630,000	157,500	472,500
San Saba	7,500,000	1,875,000	5,625,000
Williamson	17,000	4,250	12,750
Total	**66,182,000**	**16,545,500**	**49,636,500**

Water quality

Groundwater is mostly fresh with less than 1,000 milligrams per liter of total dissolved solids. Excess iron in the upper portion of the aquifer may result in poor-tasting water and may exceed drinking water standards. Additionally, naturally occurring radioactivity may exceed the state's primary drinking standards (Reedy and others, 2011) and require additional treatment or blending. Radionuclides are derived from the Precambrian granite rocks in the Llano Uplift (Reedy and others, 2011).

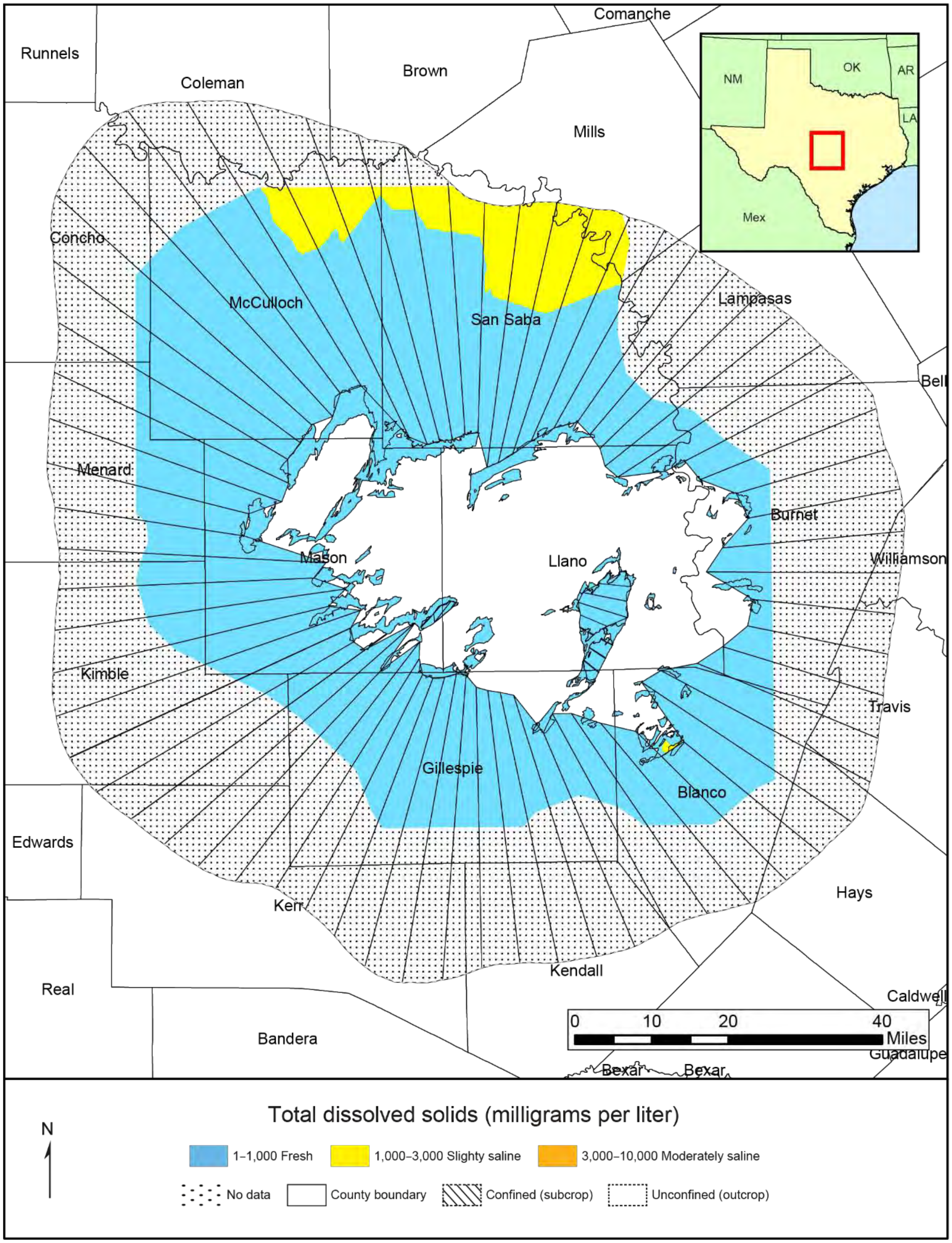


Figure 6-71. Total dissolved solids in the Hickory Aquifer.

6.19 Igneous Aquifer

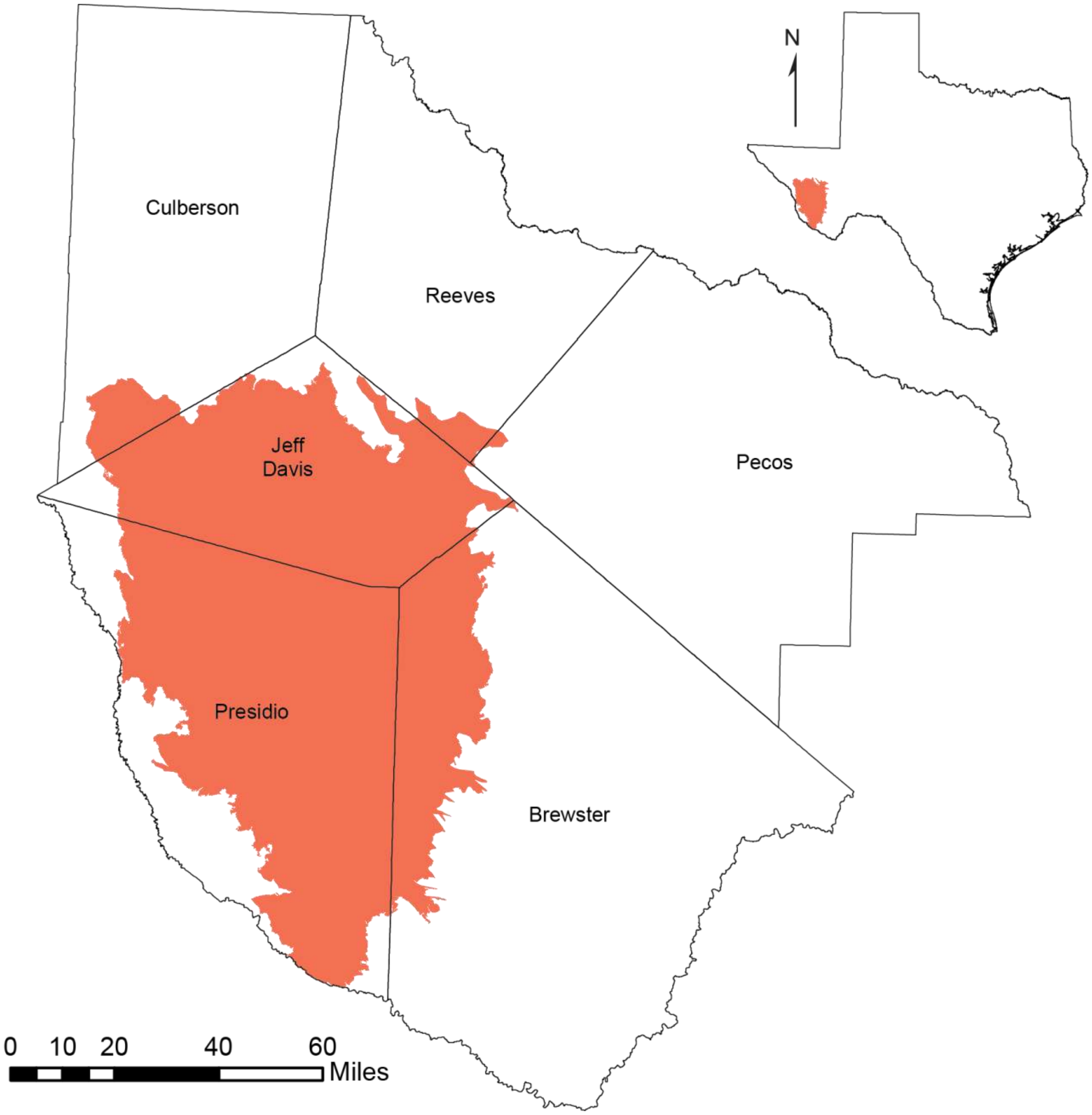


Figure 6-72. Extent of the Igneous Aquifer.

Aquifer characteristics

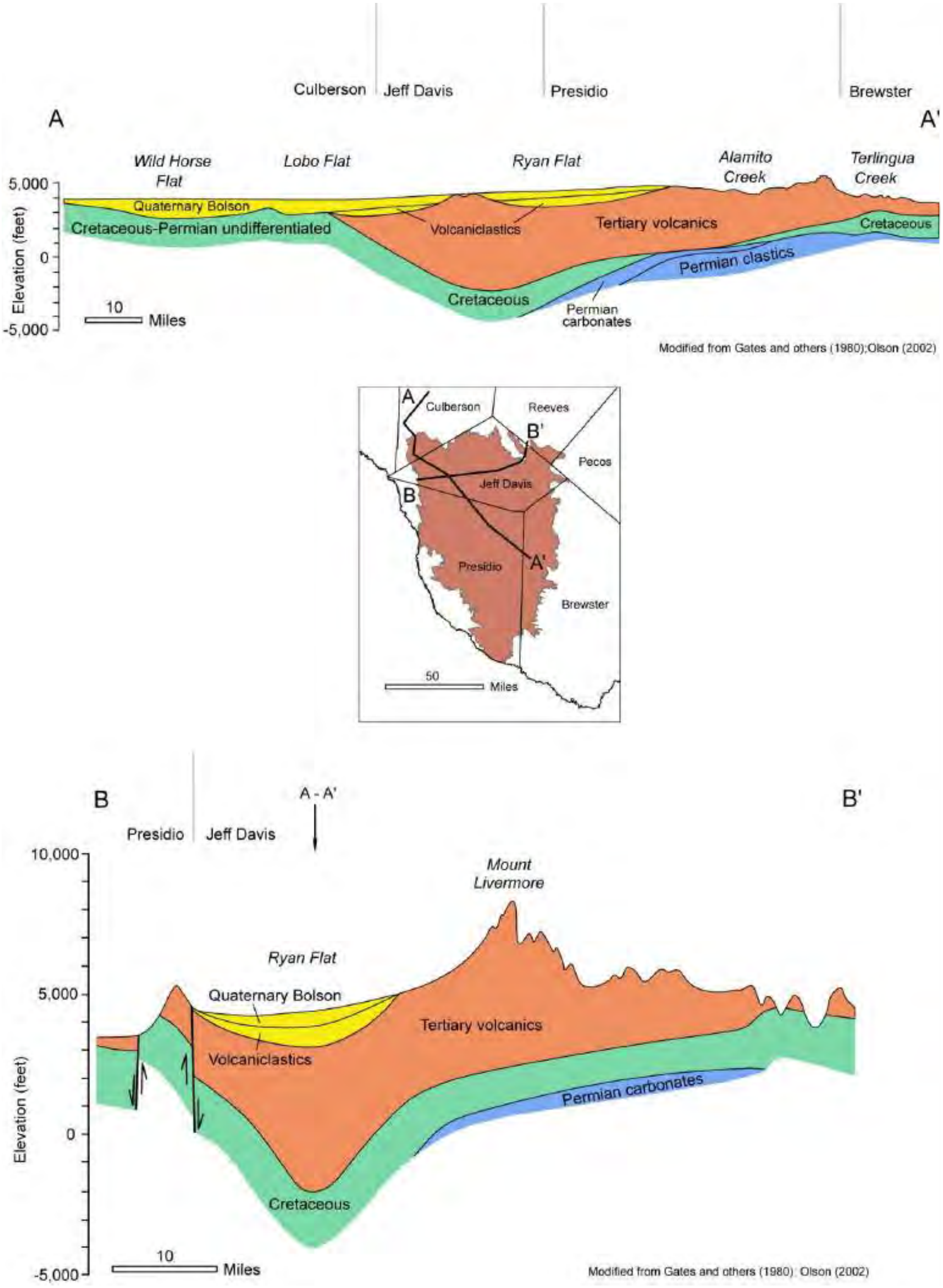
- Aquifer type: unconfined
- Area of aquifer: 6,075 square miles
- Proportion of aquifer with groundwater conservation districts: 100 percent
- Number of counties containing the aquifer: 6

Geology and hydrogeology

The Igneous Aquifer is a minor aquifer located in far west Texas (Figure 6-72). The aquifer consists of volcanic rocks made up of a complex series of welded pyroclastic rock, lava, and volcaniclastic sediments as much as 6,000 feet thick (Figure 6-73). Freshwater saturated thickness averages about 1,800 feet. The best water-bearing zones are found in igneous rocks with primary porosity and permeability, such as vesicular basalts, interflow zones in lava successions, sandstone, conglomerate, and breccia. Faulting and fracturing enhance aquifer productivity in less permeable rock units.

Flows to surface water and other aquifers

Baseflow analysis indicates that the Igneous Aquifer discharges limited amounts of groundwater to surface water in its outcrop area. Table 6-52 summarizes baseflow from the Igneous Aquifer by county. Two different groundwater availability models cover the area of the Igneous Aquifer. Both employ a no-flow boundary in the area of contact between the Igneous and West Texas Bolsons aquifers and, consequently, no modeled inter-aquifer flow between the Igneous Aquifer and other major and minor aquifers is available. An analytical approach suggests an average annual flow of approximately 3,500 acre-feet per year from the Igneous Aquifer to the Presidio-Redford Bolsons Aquifer.



Modified from Gates and others (1980);Olson (2002)

Modified from Gates and others (1980); Olson (2002)

Figure 6-73. **Structural cross-sections across the Igneous Aquifer (modified from Gates and others, 1980; Olson, 2002; Beach and others, 2004).**

Table 6-52. Summary of groundwater flow from the Igneous Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Brewster	897	3.3	0.7
Culberson	91	0.5	0.3
Jeff Davis	1,692	8.4	3.2
Pecos	9	0	0
Presidio	2,642	13	5.9
Reeves	74	0.1	0.2
Total	**5,405**	**25**	**10**

Water quantity

Total storage in the Igneous Aquifer is estimated to be more than 64 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, or about 16 million to 48 million acre-feet (Table 6-53).

Table 6-53. Total estimated recoverable storage in the Igneous Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Brewster	5,300,000	1,325,000	3,975,000
Culberson	760,000	190,000	570,000
Jeff Davis	24,000,000	6,000,000	18,000,000
Pecos	350	88	263
Presidio	34,000,000	8,500,000	25,500,000
Reeves	54,000	13,500	40,500
Total	**64,114,350**	**16,028,588**	**48,085,763**

Water quality

Water in the Igneous Aquifer is fresh and contains less than 1,000 milligrams per liter of total dissolved solids (Figure 6-74). Groundwater from some wells contains elevated levels of silica and fluoride, as a result of weathering of the igneous rock that makes up the aquifer. Groundwater in a few wells exceeds maximum contaminant levels for arsenic, fluoride, and gross alpha radiation (Reedy and others, 2011).

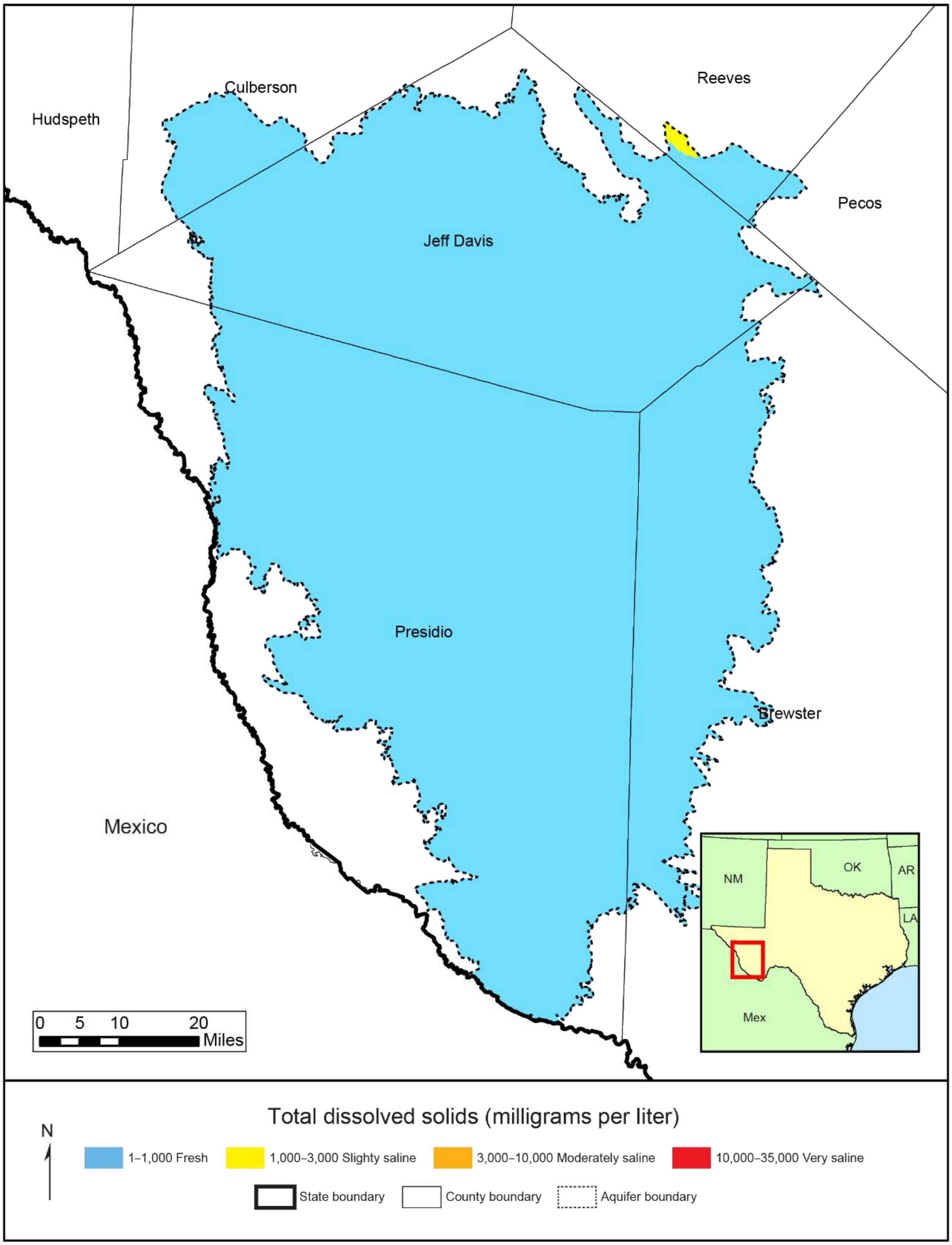


Figure 6-74. Total dissolved solids in the Igneous Aquifer.

6.20 Lipan Aquifer

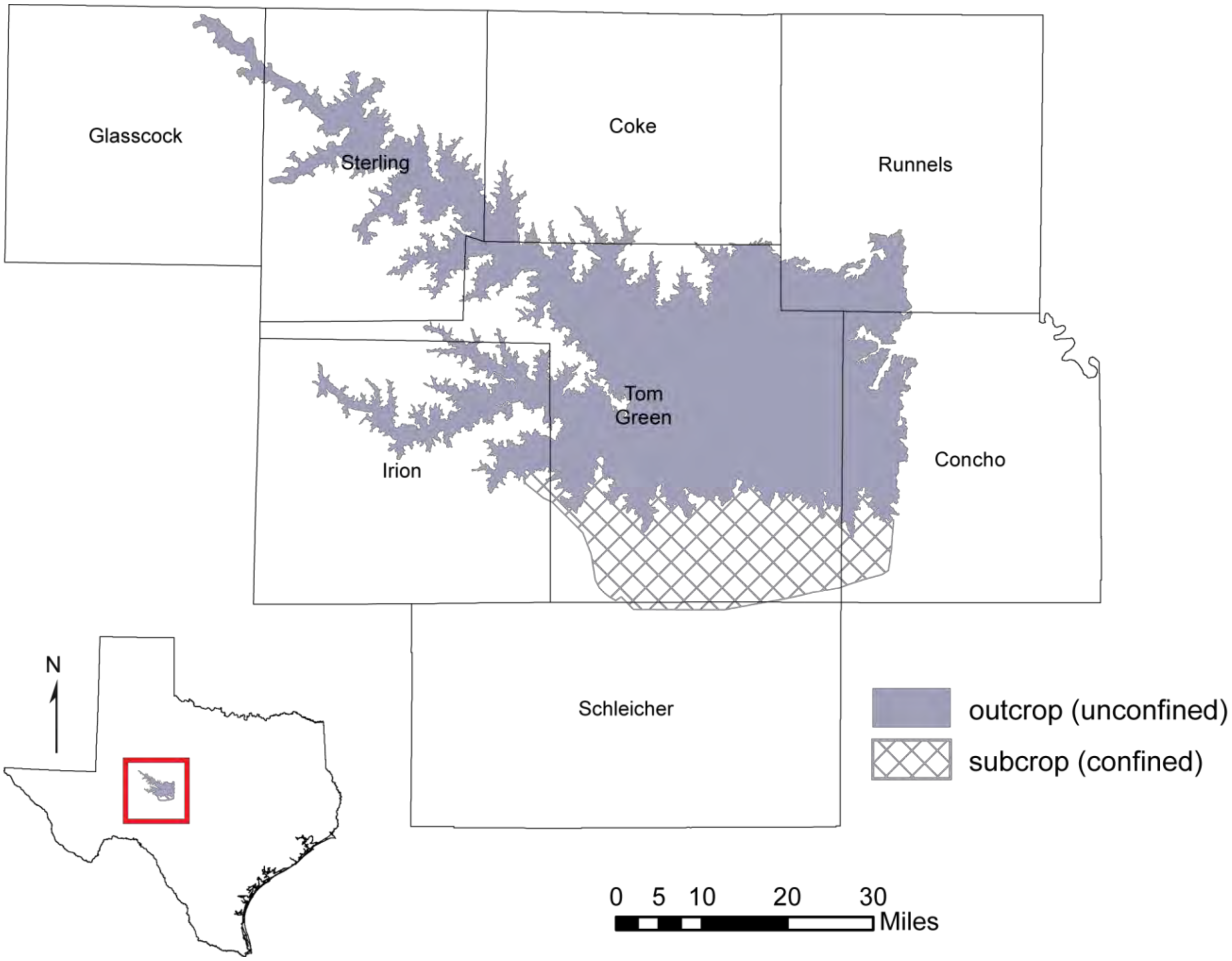


Figure 6-75. Extent of the Lipan Aquifer.

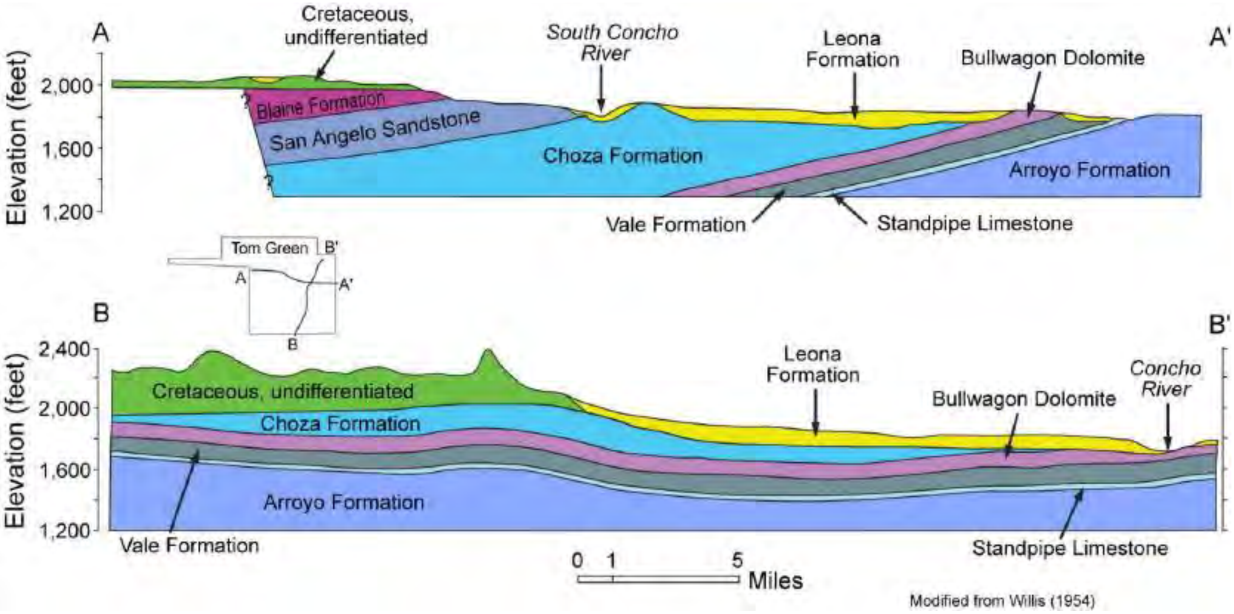
Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 1,571 square miles
- Area in subsurface: 424 square miles
- Proportion of aquifer with groundwater conservation districts: 85 percent
- Number of counties containing the aquifer: 8

Geology and hydrogeology

The Lipan Aquifer is a minor aquifer in west central Texas (Figure 6-75). The aquifer includes water-bearing alluvium and the up-dip portions of older strata underlying the alluvium. The alluvium includes as much as 125 feet of saturated sediments of the Quaternary Leona Formation. These deposits consist mostly of gravels and conglomerates cemented with sandy lime and layers of clay. The formation generally fines upward with conglomerates existing mainly in locations of thicker alluvium. The underlying strata include the San Angelo Sandstone of the Pease River Group and the Choza Formation, Bullwagon Dolomite, Vale Formation, Standpipe Limestone, and Arroyo Formation of the Permian-age Clear Fork Group (Figure 6-76). These units are predominantly limestones and shales.

The alluvial deposits and the upper parts of the older rocks are hydraulically connected. Groundwater flow in the Lipan Aquifer does not appear to be structurally controlled. Higher-production wells appear to correspond to alluvial deposits overlying the Choza, Bullwagon, and Vale formations. In these areas, thick alluvial deposits with conglomerates lie near the contact with the Permian formations.



Modified from Willis (1954)

Figure 6-76. **Structural cross-sections across the Lipan Aquifer in Tom Green County, Texas. A-A′, west to east; B-B′, south to north (modified from Willis, 1954).**

Flows to surface water and other aquifers

The Concho River is a major discharge and recharge feature of the Lipan Aquifer. However, net discharge from the Lipan Aquifer in the form of river baseflow is fairly small, and during a recent drought the Concho River flow ceased between San Angelo and Paint Rock (Beach and others, 2004). Table 6-54 shows a summary of baseflow in the outcrop areas of the Lipan Aquifer.

Table 6-55 shows groundwater availability model estimates of total flow and average annual flow between the Lipan Aquifer and other aquifers. Groundwater flows from the Edwards-Trinity (Plateau) Aquifer to the Lipan Aquifer in Coke, Irion, Runnels, and Schleicher counties, while in Concho and Tom Green counties the flow direction is reversed.

Table 6-54. Summary of groundwater flow from the Lipan Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Coke	37	0.2	0.1
Concho	153	0.9	0.3
Glasscock	19	0	0
Irion	151	2.2	1.1
Runnels	88	0.3	0
Sterling	203	0.7	0.4
Tom Green	920	7.1	2.1
Total	**1,571**	**11**	**4**

Table 6-55. Model estimates of inter-aquifer flows between the Lipan Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Lipan Aquifer	Edwards-Trinity (Plateau) Aquifer & Other Formations	7,506
Edwards-Trinity (Plateau) Aquifer & Other Formations	Lipan Aquifer	7,507

Water quantity

Total storage in the Lipan Aquifer is estimated to be about 4 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 1 million to 3.1 million acre-feet (Table 6-56).

Table 6-56. Total estimated recoverable storage in the Lipan Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Coke	13,000	3,250	9,750
Concho	720,000	180,000	540,000
Glasscock	6,000	1,500	4,500
Irion	100,000	25,000	75,000
Runnels	400,000	100,000	300,000
Schleicher	7,500	1,875	5,625
Sterling	41,000	10,250	30,750
Tom Green	2,900,000	725,000	2,175,000
Total	**4,200,000**	**1,046,875**	**3,140,625**

Water quality

Water quality in the alluvium is very hard and ranges from fresh to slightly saline, containing between 350 and 3,000 milligrams per liter of total dissolved solids (Figure 6-77). Water in the underlying parts of the Choza Formation and Bullwagon Dolomite tends to be moderately saline with total dissolved solids in excess of 3,000 milligrams per liter. The central region of the aquifer has a high probability of exceeding the maximum contaminant level for total dissolved solids. The eastern portion of the aquifer has the highest probability of exceeding the maximum contaminant level for nitrate (Reedy and others, 2011).

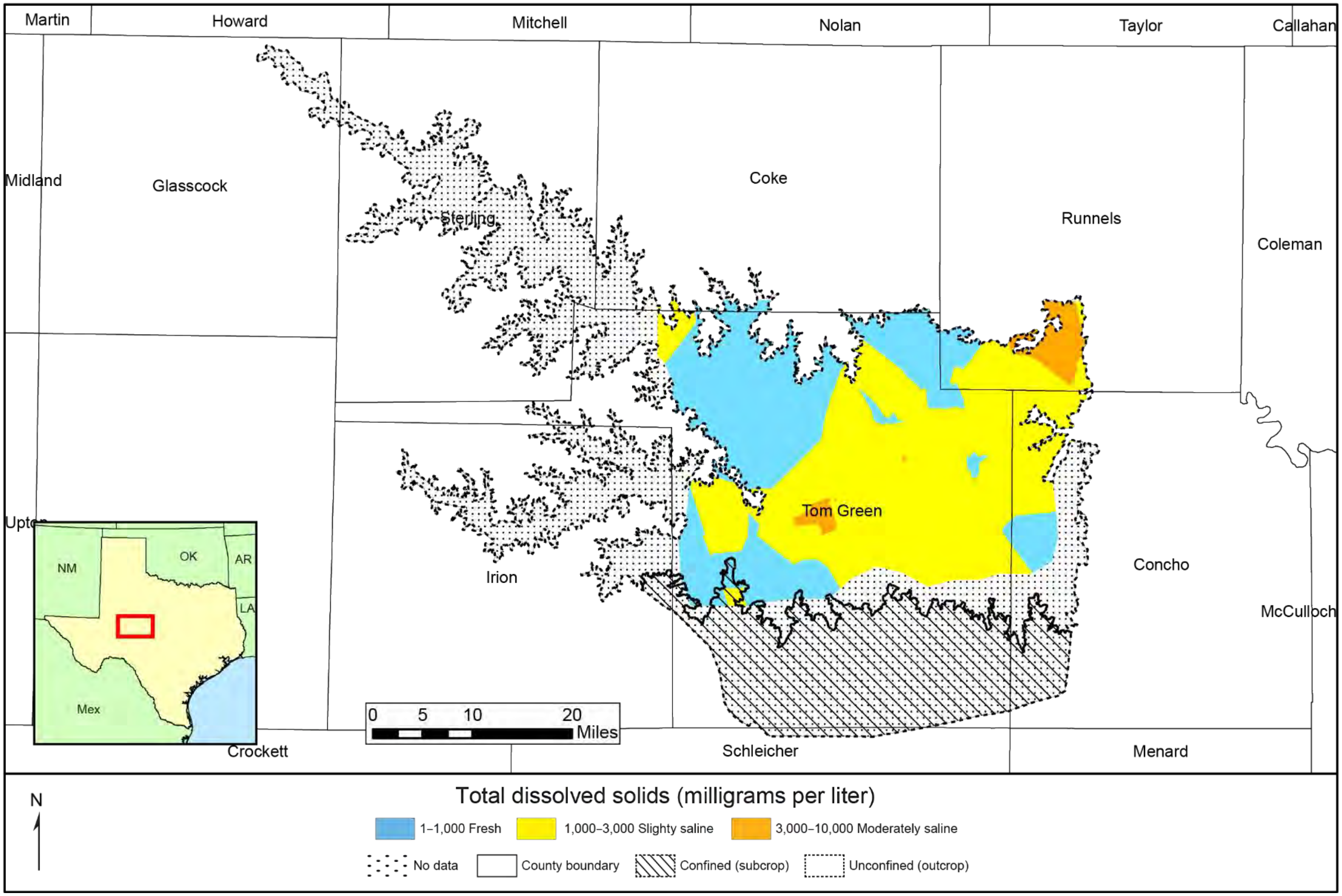


Figure 6-77. Total dissolved solids in the Lipan Aquifer.

6.21 Marathon Aquifer

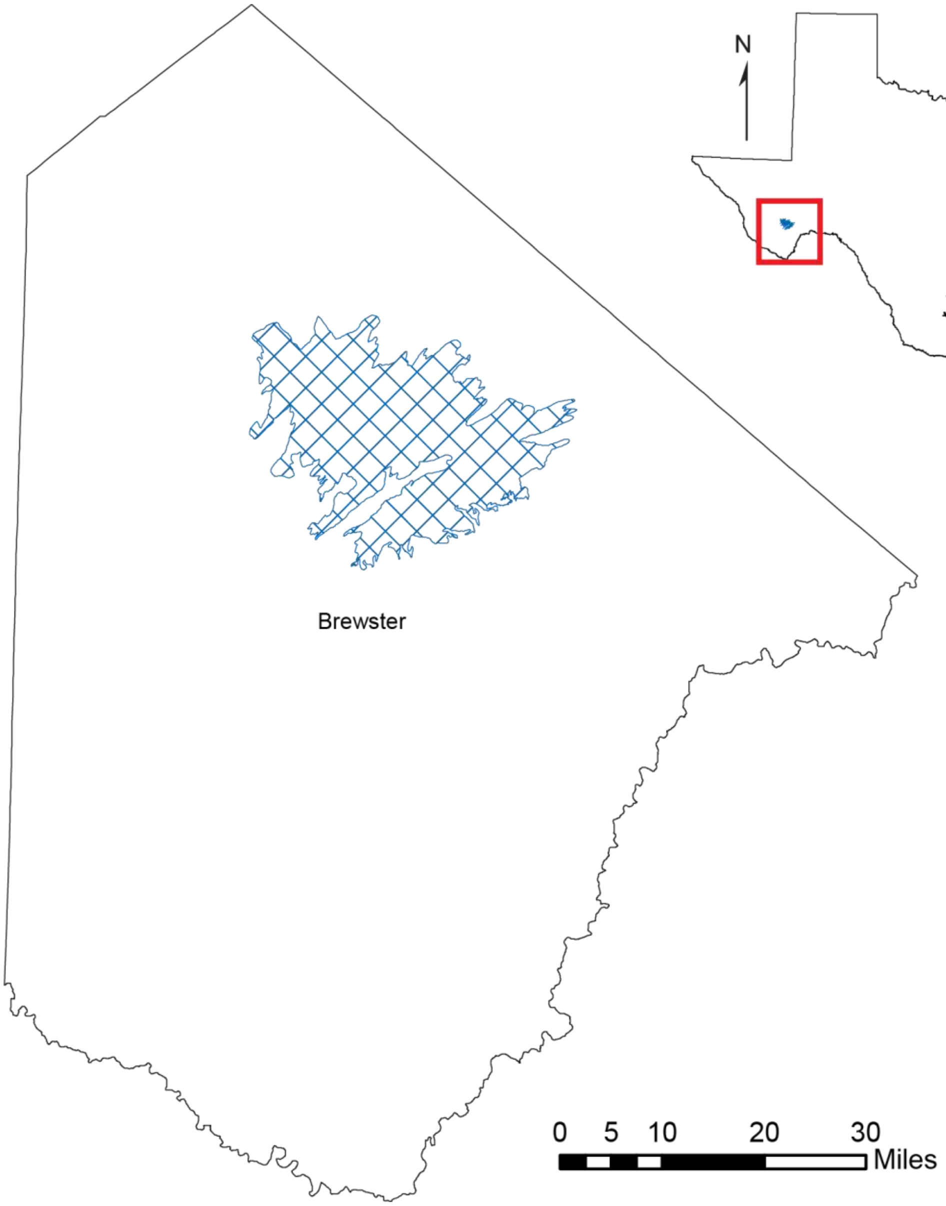


Figure 6-78. **Extent of the Marathon Aquifer.**

Aquifer characteristics

- Aquifer type: unconfined with locally confined areas
- Area of outcrop: 391 square miles
- Proportion of aquifer with groundwater conservation districts: 100 percent
- Number of counties containing the aquifer: 1

Geology and hydrogeology

The Marathon Aquifer, a minor aquifer, occurs entirely within north central Brewster County (Figure 6-78). The aquifer consists of tightly folded and faulted rocks of the Gaptank Formation, the Dimple Limestone, the Tesnus Formation, the Caballos Novaculite, the Maravillas Chert, the Fort Peña Formation, and the Marathon Limestone (Figure 6-79). Although the maximum thickness of the aquifer is about 900 feet, well depths are commonly less than 250 feet. Water in the aquifer is generally under unconfined conditions and is contained in fractures, joints, and cavities in the limestone. Groundwater is locally confined in areas where the aquifer is buried beneath impermeable formations, such as in the town of Marathon, and may rise a few feet above the depth at which it is first encountered. The Marathon Limestone is the most productive part of the aquifer. Many of the shallow wells in the region actually produce water from alluvial deposits that cover parts of the rock formations. Well yields range from less than 10 gallons per minute to more than 300 gallons per minute; the highest yields occur within a fault zone in the town of Marathon (Smith, 2001).

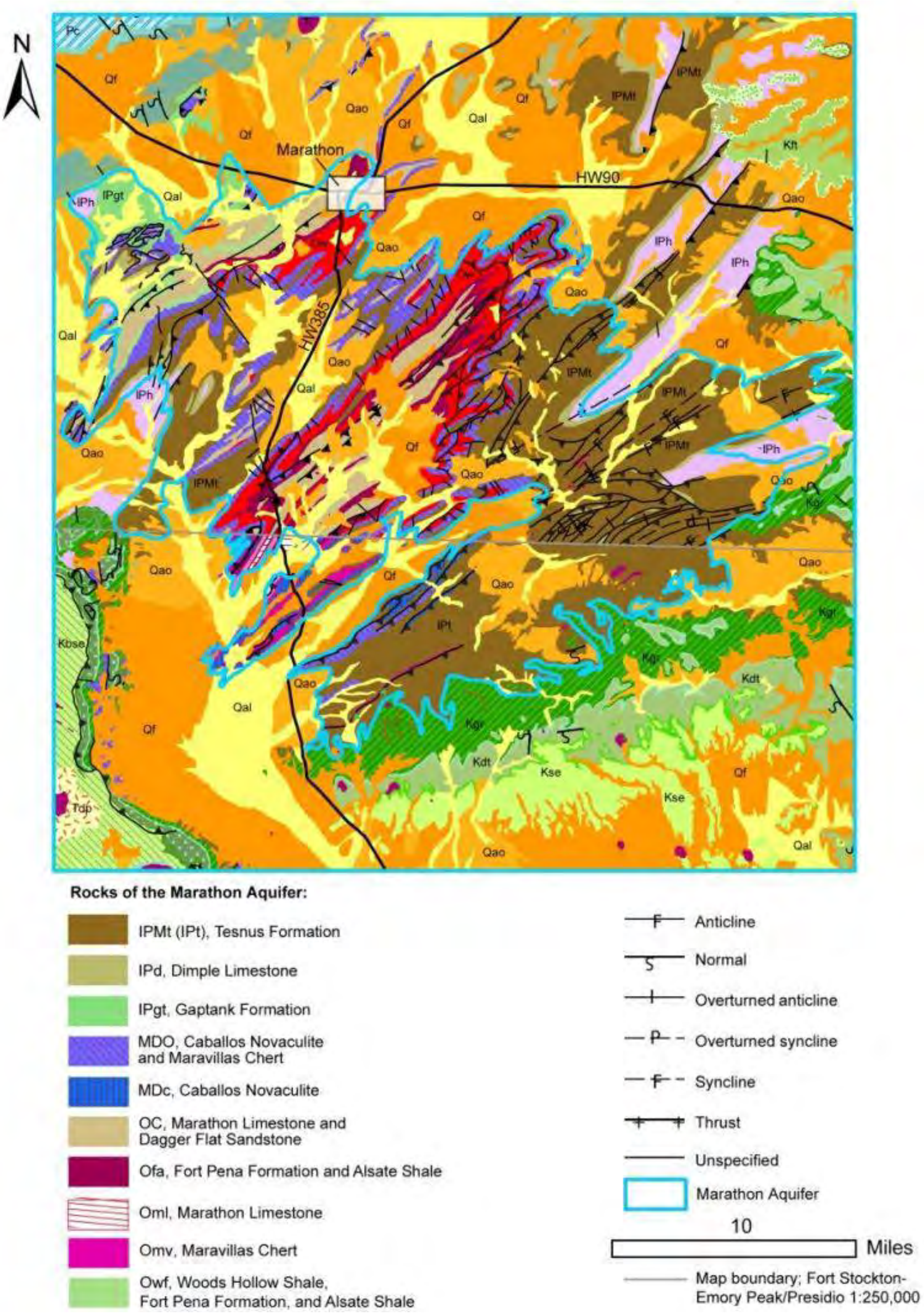


Figure 6-79. **Geologic map across the Marathon Aquifer (USGS and TWDB, 2006).**

Flows to surface water and other aquifers

Table 6-57 summarizes baseflow from the Marathon Aquifer. The Marathon Aquifer discharges at Peña Colorada Springs near Marathon, and at smaller springs along creeks in the area. The Marathon Aquifer is not in contact with any other major or minor aquifers; consequently, no inter-aquifer flows are expected.

Table 6-57. Summary of groundwater flow from the Marathon Aquifer to surface water.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Brewster	391	2.8	1

Water quantity

Total storage in the Marathon Aquifer is estimated to be 1.5 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 375,000 to 1.1 million acre-feet (Table 6-58).

Table 6-58. Total estimated recoverable storage in the Marathon Aquifer.

County	Total storage	25 percent of storage	75 percent of storage
Brewster	1,500,000	375,000	1,125,000

Water quality

Total dissolved solids range from 500 to 1,000 milligrams per liter, and the water, although very hard, is generally suitable for most uses (Figure 6-80).

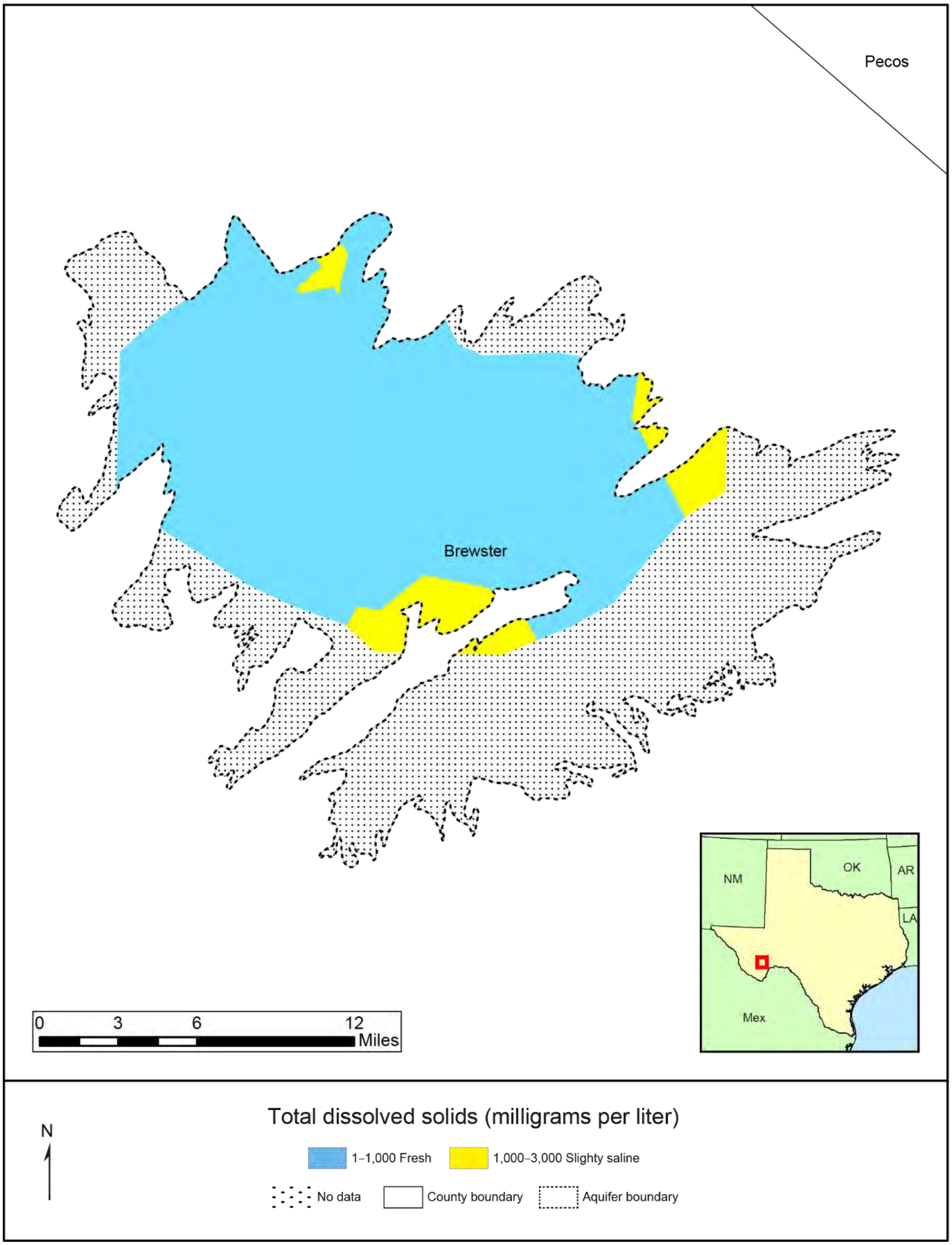


Figure 6-80. Total dissolved solids in the Marathon Aquifer.

6.22 Marble Falls Aquifer

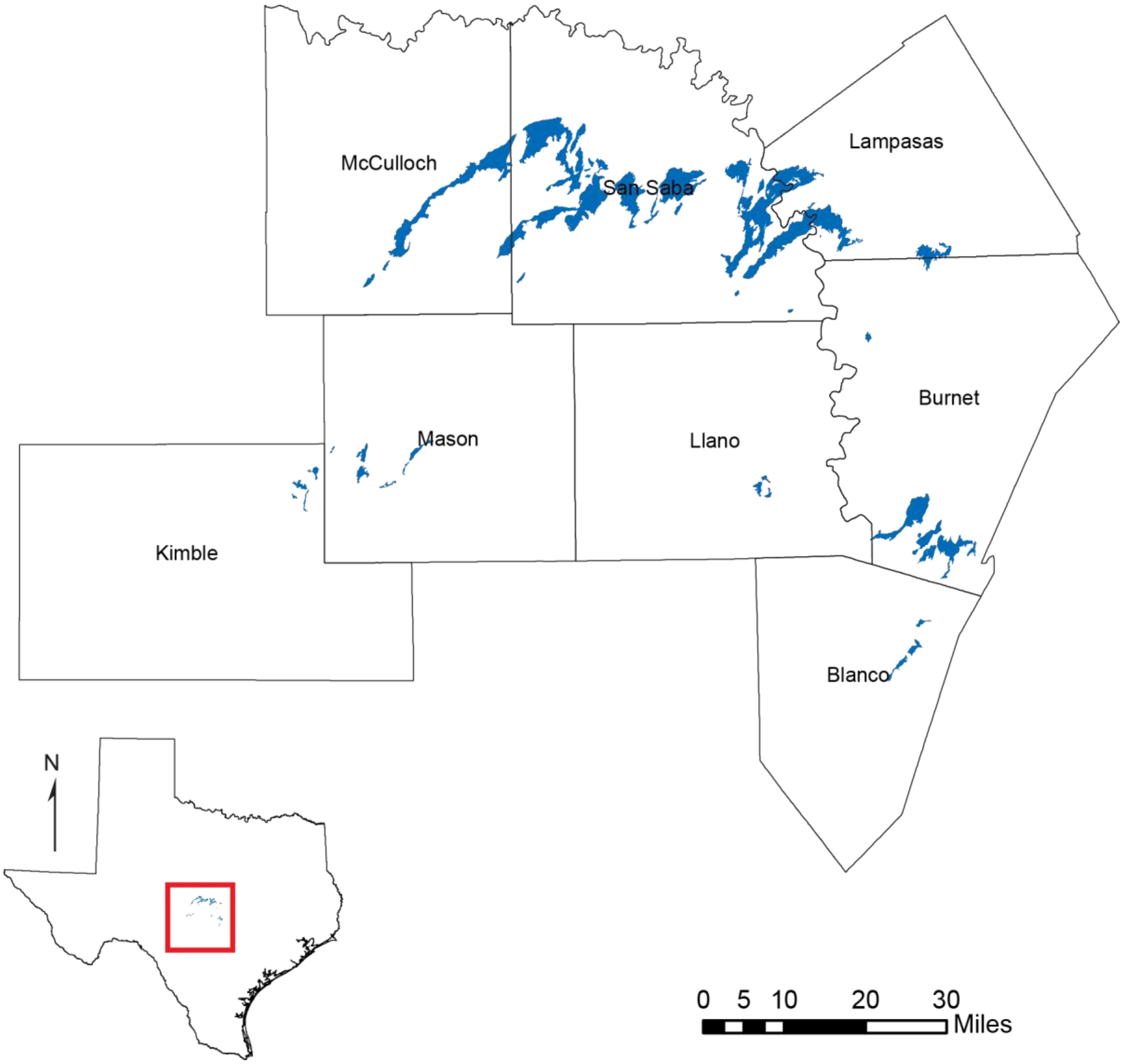


Figure 6-81. Extent of the Marble Falls Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of outcrop: 215 square miles
- Proportion of aquifer with groundwater conservation districts: 78 percent
- Number of counties containing the aquifer: 8

Geology and hydrogeology

The Marble Falls Aquifer is a minor aquifer that occurs in several separated outcrops along the northern and eastern edges of the Llano Uplift in Central Texas (Figure 6-81). The subsurface extent of the aquifer is largely unknown. Water occurs in the Marble Falls Limestone in voids and fractures, and the formation is very permeable in some areas. Wells may produce up to 2,000 gallons per minute and the formation measures up to 600 feet thick with an average estimated thickness of 160 feet. Specific yield estimates range from 1.5 percent to as much as 3 percent.

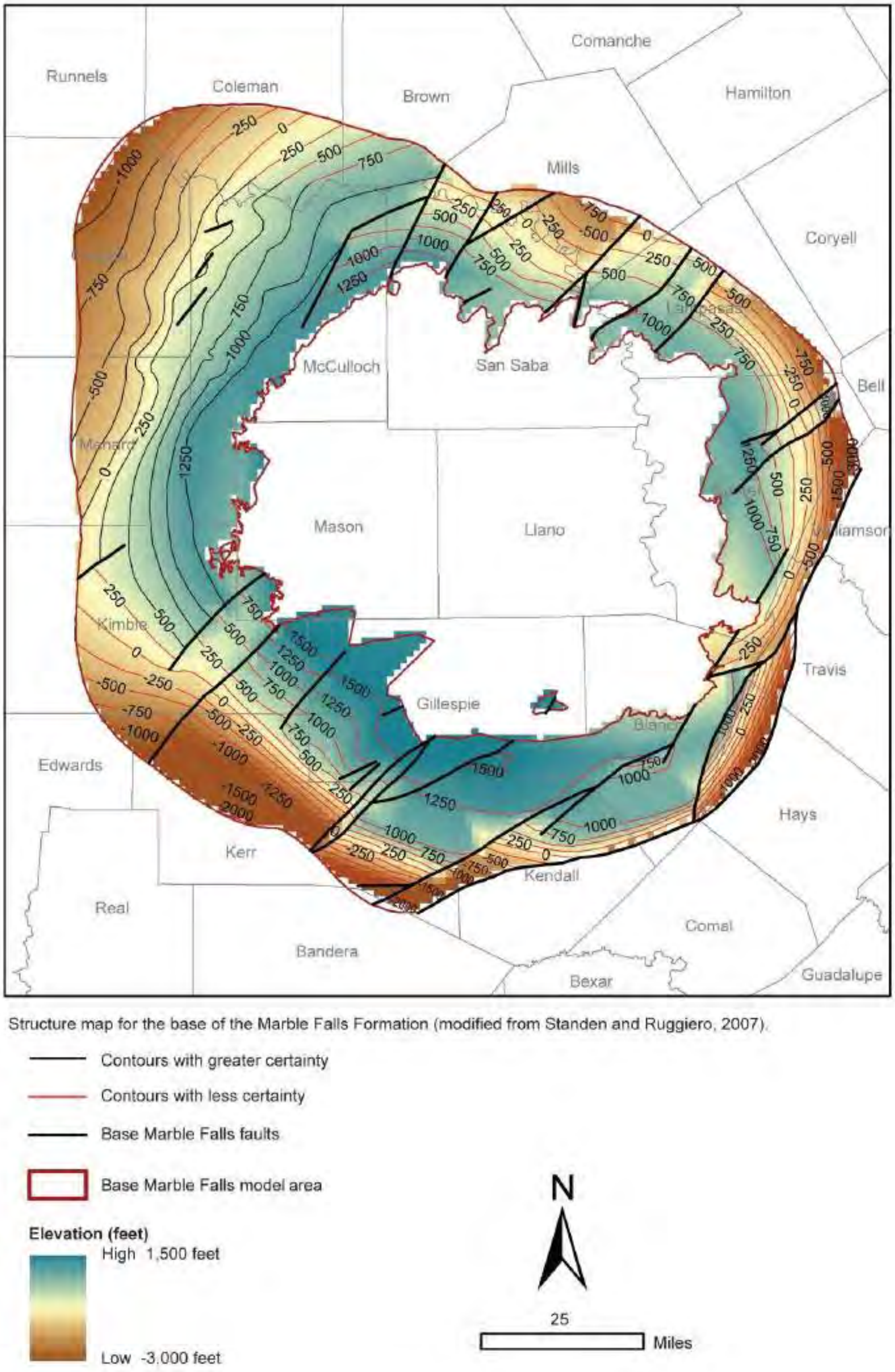


Figure 6-82. **Structure map for the base of the Marble Falls Formation (modified from Standen and Ruggiero, 2007).**

Flows to surface water and other aquifers

Numerous large springs originate from the Marble Falls Aquifer and provide a significant part of the baseflow to the San Saba River in McCulloch and San Saba counties and to the Colorado River in San Saba and Lampasas counties. Table 6-59 shows a summary of baseflow in the outcrop areas of the Marble Falls Aquifer. Where underlying beds are thin or absent, the Marble Falls Aquifer may be hydraulically connected to the Ellenburger-San Saba Aquifer. Table 6-60 shows groundwater availability model analysis estimates of total flow and average annual flow between the Marble Falls Aquifer and other aquifers.

Table 6-59. Summary of groundwater flow from the Marble Falls Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Burnet	23	1.4	0.3
Kimble	2	0.1	0
Lampasas	20	0.6	0.1
Llano	2	0.1	0
Mason	5	0.1	0
McCulloch	28	0.5	0.1
San Saba	125	3.3	0.7
Total	**205**	**6.1**	**1.2**

Table 6-60. Model estimates of inter-aquifer flows between the Marble Falls Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Marble Falls Aquifer	Ellenburger-San Saba Aquifer	3,647
Edwards-Trinity (Plateau) Aquifer	Marble Falls Aquifer	7
Ellenburger-San Saba Aquifer	Marble Falls Aquifer	2,368
Trinity Aquifer	Marble Falls Aquifer	144

Water quantity

Total storage in the Marble Falls Aquifer is estimated to be about 265,000 acre-feet. Recoverable storage is estimated to be between 25 and 75 of the total, about 66,000 to 198,000 acre-feet (Table 6-61).

Table 6-61. Total estimated recoverable storage in the Marble Falls Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Blanco	1,300	325	975
Burnet	38,000	9,500	28,500
Kimble	2,400	600	1,800
Lampasas	39,000	9,750	29,250
Llano	2,100	525	1,575
Mason	5,300	1,325	3,975
McCulloch	33,000	8,250	24,750
San Saba	144,000	36,000	108,000
Total	**265,100**	**66,275**	**198,825**

Water quality

The water quality in the Marble Falls Aquifer is variable, with the total dissolved solids content increasing down-dip to the north, away from the Llano Uplift. Because the limestone beds composing this aquifer are relatively shallow, the aquifer is susceptible to pollution by surface uses and activities. For example, some wells in Blanco County have produced water with high nitrate concentrations. In the subsurface, groundwater becomes highly mineralized; however, the water produced from this aquifer is suitable for most purposes and generally contains less than 1,000 milligrams per liter of total dissolved solids (Figure 6-83).

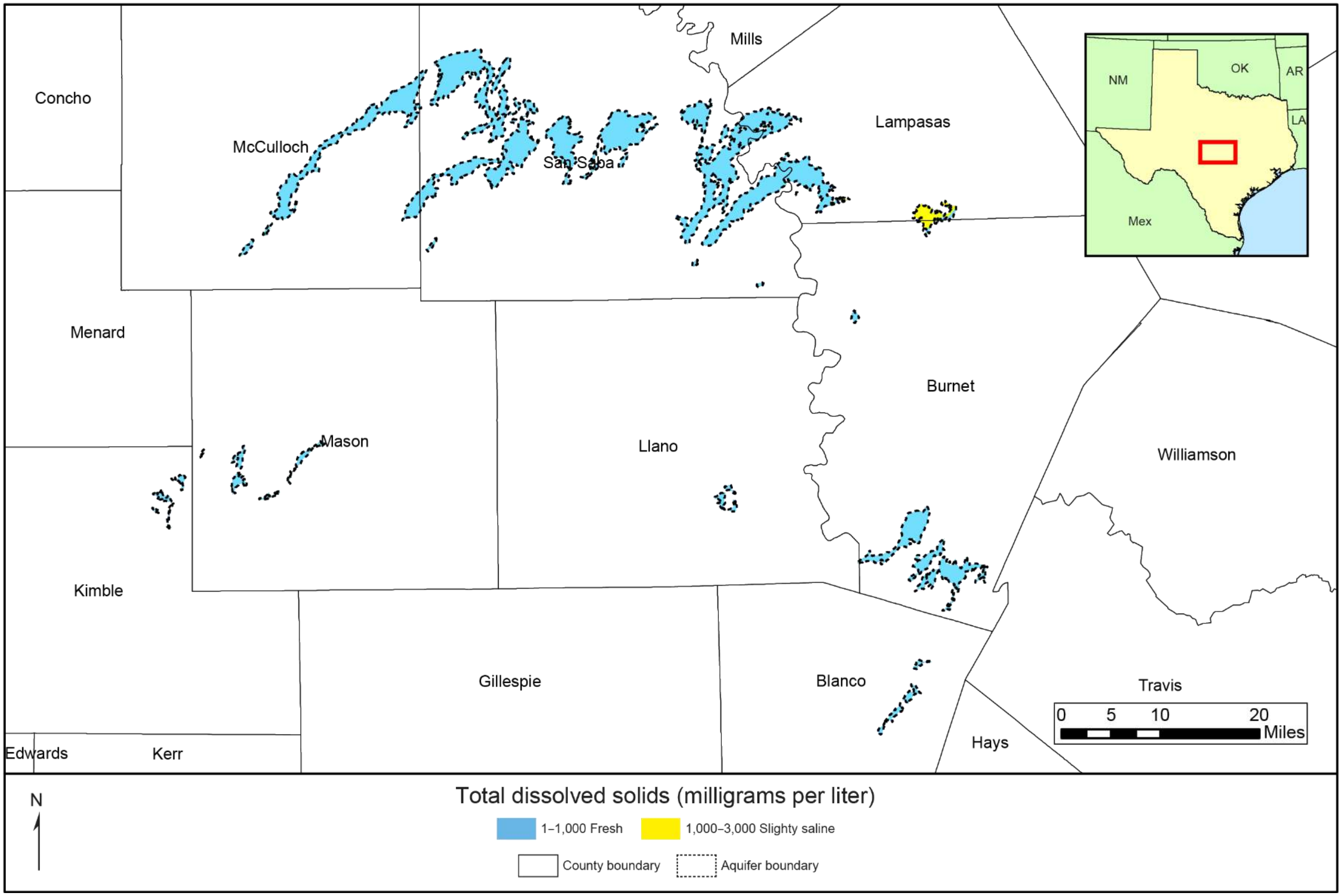


Figure 6-83. Total dissolved solids in the Marble Falls Aquifer.

6.23 Nacatoch Aquifer

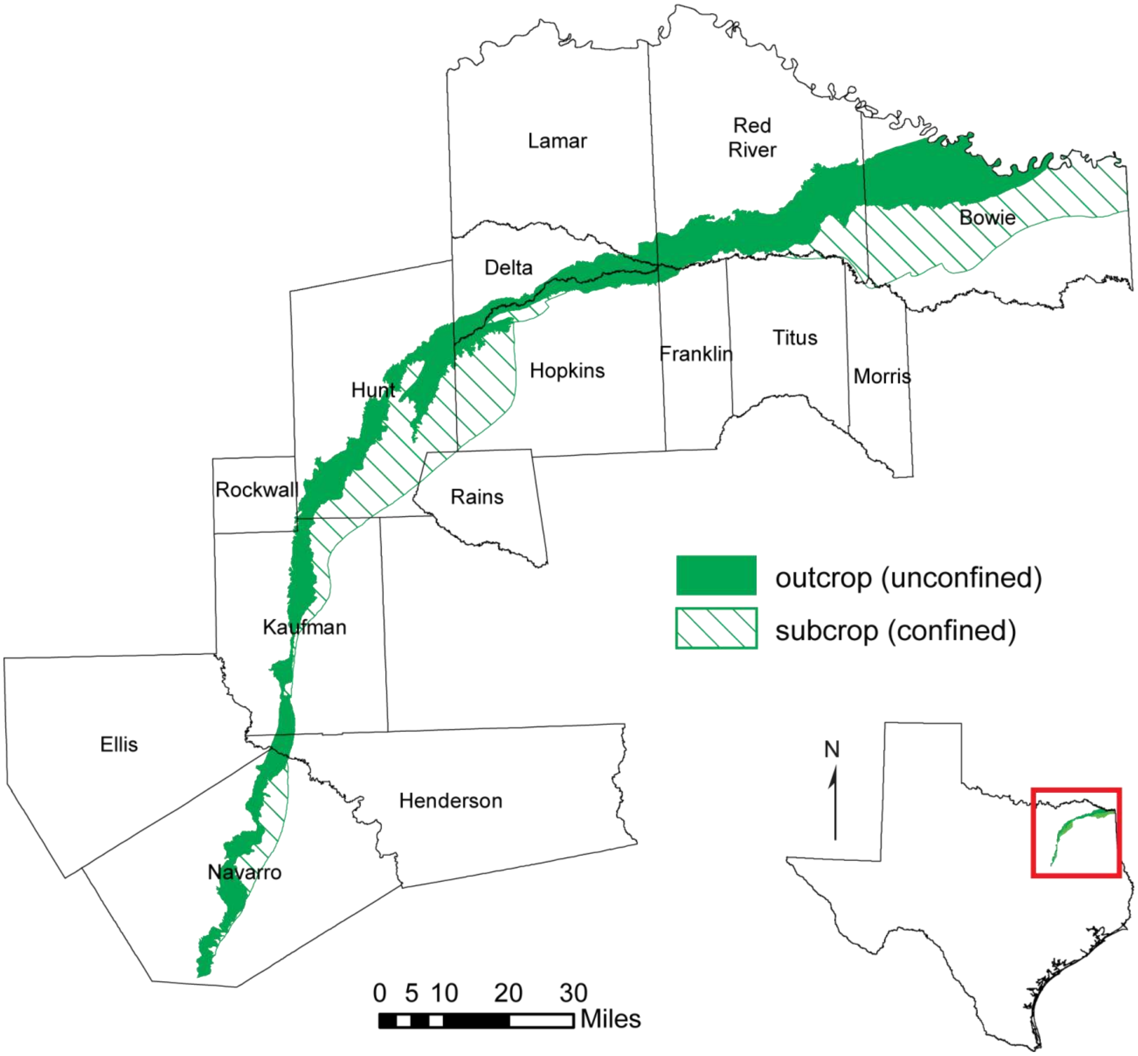


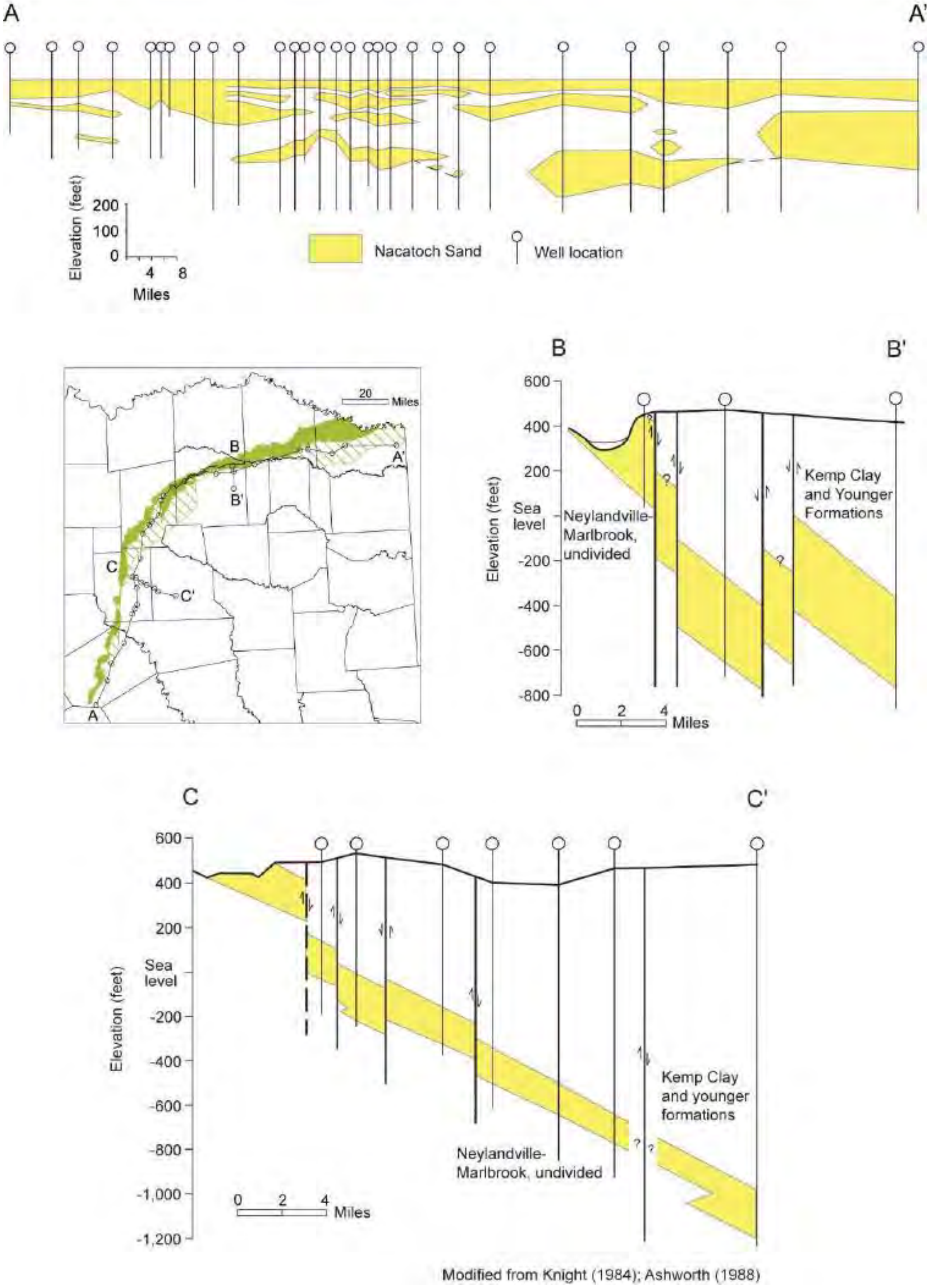
Figure 6-84. Extent of the Nacatoch Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 891 square miles
- Area in subsurface: 939 square miles
- Proportion of aquifer with groundwater conservation districts: 0.5 percent
- Number of counties containing the aquifer: 15

Geology and hydrogeology

The Nacatoch Aquifer is a minor aquifer that occurs in a narrow band across northeast Texas (Figure 6-84). The aquifer consists of the Nacatoch Sand, which is composed of sequences of sandstone separated by impermeable layers of mudstone or clay (Figure 6-85). These sandstones are marine in origin, coarsen upward, and are laterally discontinuous. The number of sand layers varies throughout the aquifer's extent, and the thickness of individual sand units ranges from more than 100 feet in the north to less than 20 feet to the south. The thickness of intervening mudstone units similarly ranges from more than 100 feet to only a few feet. Freshwater saturated thickness averages about 50 feet. The aquifer also includes a hydraulically connected cover of alluvium that is as much as 80 feet thick along major drainages. Groundwater in this aquifer is usually under artesian conditions except in shallow wells where the Nacatoch Formation crops out and water table conditions exist. The Mexia-Talco Fault Zone generally delineates the subsurface limit of the aquifer.



Modified from Knight (1984); Ashworth (1988)

Figure 6-85. **Structural cross-sections across the Nacatoch Aquifer (modified from Knight, 1984; Ashworth, 1988).**

Flows to surface water and other aquifers

The Nacatoch Aquifer discharges to surface water and springs in the outcrop areas. Some springs fed by the Nacatoch dried up in the 1920s when pumping began in their vicinity, but in other areas of the aquifer where pumping has been minimal, springflow is likely to have been maintained (Beach and others, 2009). Table 6-62 shows a summary of baseflow in the outcrop areas of the Nacatoch Aquifer. Groundwater availability model analysis does not estimate any inter-aquifer flow between the Nacatoch Aquifer and other major and minor aquifers.

Table 6-62. Summary of groundwater flow from the Nacatoch Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Bowie	198	38.3	11.1
Delta	64	3.6	0.2
Ellis	<1	0	0
Franklin	6	0.6	0
Henderson	9	0.6	0.1
Hopkins	61	3.5	0.2
Hunt	155	6.2	0.2
Kaufman	77	6.3	0.6
Lamar	11	1	0.1
Navarro	88	5	0.3
Red River	221	28.5	3.7
Rockwall	1	0.1	0
Titus	<1	0	0
Total	**630**	**94**	**17**

Water quantity

Total storage in the Nacatoch Aquifer is estimated to be more than 4 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, or about 1 million to 3 million acre-feet (Table 6-63).

Table 6-63. Total estimated recoverable storage in the Nacatoch Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Bowie	240,000	560,000	1,680,000
Delta	100,000	25,000	75,000
Ellis	66	17	50
Franklin	7,300	1,825	5,475
Henderson	9,800	2,450	7,350
Hopkins	330,000	82,500	247,500
Hunt	550,000	137,500	412,500
Kaufman	120,000	30,000	90,000
Lamar	12,000	3,000	9,000
Morris	2,900	725	2,175
Navarro	95,000	23,750	71,250
Rains	18,000	4,500	13,500
Red River	591,000	147,750	443,250
Rockwall	280	70	210
Titus	15,000	3,750	11,250
Total	**4,091,346**	**1,022,837**	**3,068,510**

Water quality

Groundwater in the aquifer is typically alkaline, high in sodium bicarbonate, and soft. Total dissolved solids are significantly higher down-dip south of the Mexia-Talco Fault Zone, where the water contains between 1,000 and 3,000 milligrams per liter of total dissolved solids (Figure 6-86).

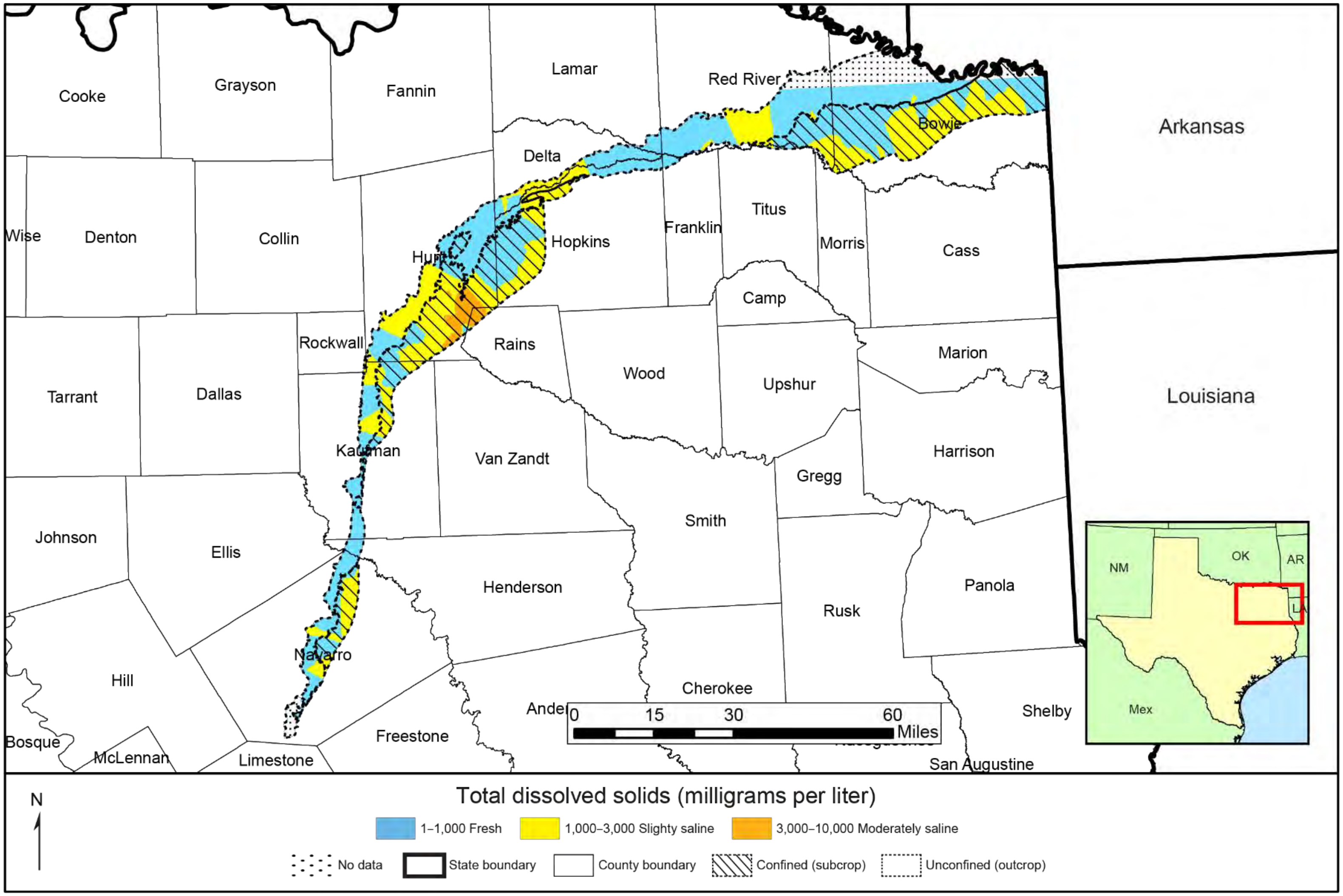


Figure 6-86. Total dissolved solids in the Nacatoch Aquifer.

6.24 Queen City Aquifer

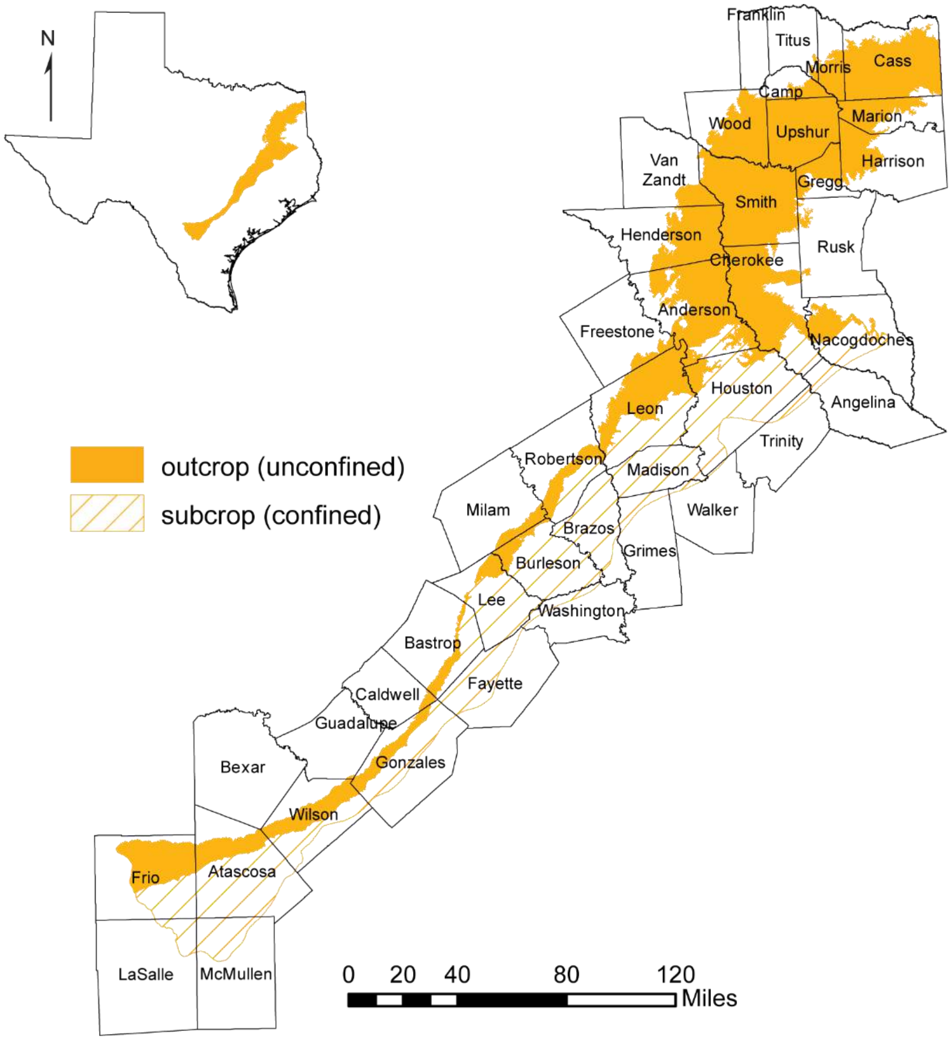


Figure 6-87. Extent of the Queen City Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 8,781 square miles
- Area in subsurface: 7,015 square miles
- Proportion of aquifer with groundwater conservation districts: 63 percent
- Number of counties containing the aquifer: 42

Geology and hydrogeology

The Queen City Aquifer is a minor, widespread aquifer that stretches across the upper coastal plain of Texas (Figure 6-87). Water is stored in sand, loosely cemented sandstone, and interbedded clay layers of the Queen City Formation, which reaches 2,000 feet in thickness in south Texas (Figure 6-88). The average freshwater saturated thickness of the Queen City Aquifer is about 140 feet.

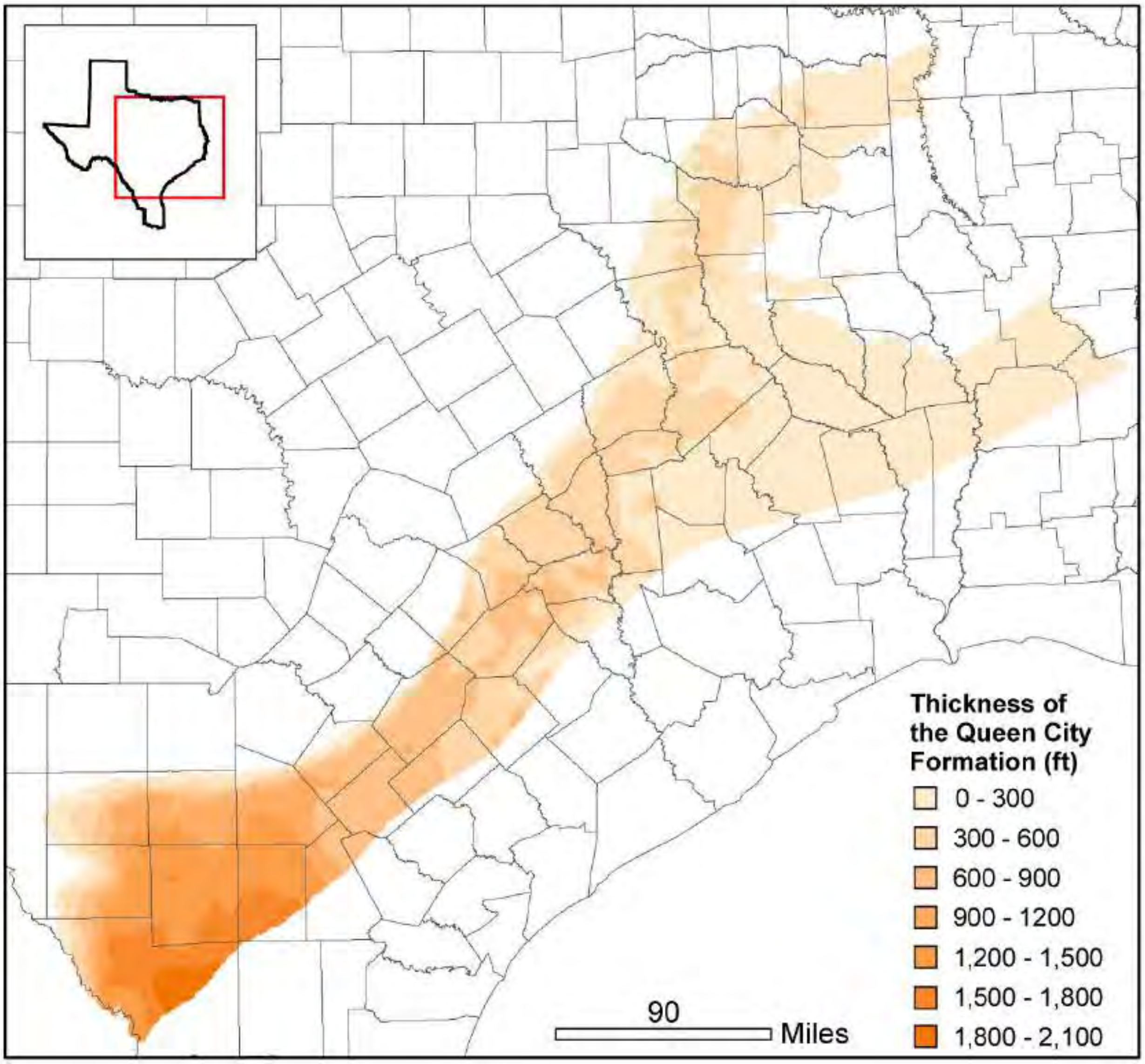


Figure 6-88. Thickness of the Queen City Aquifer (from Kelley and others, 2004).

Flows to surface water and other aquifers

The Queen City Aquifer discharges to streams, springs, and other formations. Table 6-64 shows a summary of baseflow in the outcrop areas of the Queen City Aquifer. Groundwater availability model analysis does not estimate any inter-aquifer flow between the Queen City Aquifer and other major and minor aquifers.

Table 6-64. Summary of groundwater flow from the Queen City Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Anderson	724	108.9	29.8
Atascosa	185	15.5	5.5
Bastrop	83	5.5	1.8
Bexar	0	0	0
Burleson	75	4.1	0.6
Caldwell	21	2.4	0.8
Camp	82	17.8	4
Cass	747	242.3	77.7
Cherokee	668	138.3	42.7
Franklin	1	0.2	0
Freestone	59	6.5	1.4
Frio	381	14.8	4.7
Gonzales	144	13.1	4
Gregg	169	41.8	13.6
Guadalupe	2	0.2	0.1
Harrison	238	66.4	18.1
Henderson	434	46	7.2
Houston	101	19.6	6.3
Lee	65	3.8	0.6
Leon	517	62.4	15.3
Marion	239	77	22.9
Milam	74	4.8	0.7
Morris	133	28	5.7
Nacogdoches	157	47.8	15.6
Robertson	109	6.6	0.6
Rusk	30	10	3.7
Smith	894	202	62

Table 6-64 (continued). Summary of groundwater flow from the Queen City Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Titus	18	3.8	0.6
Upshur	593	150.7	44.6
Van Zandt	102	16.1	3.8
Wilson	227	18.1	6.7
Wood	411	77.2	20
Total	**7,683**	**1,452**	**421**

Water quantity

Total storage in the Queen City Aquifer is estimated to be more than 539 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 134.8 million to 404.4 million acre-feet (Table 6-65).

Table 6-65. Total estimated recoverable storage in the Queen City Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Anderson	19,000,000	4,750,000	14,250,000
Angelina	2,000,000	500,000	1,500,000
Atascosa	83,000,000	20,750,000	62,250,000
Bastrop	9,500,000	2,375,000	7,125,000
Brazos	25,000,000	6,250,000	18,750,000
Burleson	29,000,000	7,250,000	21,750,000
Caldwell	430,000	107,500	322,500
Camp	600,000	150,000	450,000
Cass	8,000,000	2,000,000	6,000,000
Cherokee	15,000,000	3,750,000	11,250,000
Fayette	19,640,000	4,910,000	14,730,000
Freestone	290,000	72,500	217,500
Frio	45,000,000	11,250,000	33,750,000
Gonzales	26,000,000	6,500,000	19,500,000
Gregg	1,500,000	375,000	1,125,000
Grimes	4,970,000	1,242,500	3,727,500

Table 6-65 (continued). Total estimated recoverable storage in the Queen City Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Harrison	1,200,000	300,000	900,000
Henderson	6,700,000	1,675,000	5,025,000
Houston	37,000,000	9,250,000	27,750,000
La Salle	15,000,000	3,750,000	11,250,000
Lee	23,000,000	5,750,000	17,250,000
Leon	25,000,000	6,250,000	18,750,000
Madison	20,000,000	5,000,000	15,000,000
Marion	2,500,000	625,000	1,875,000
McMullen	33,000,000	8,250,000	24,750,000
Milam	650,000	162,500	487,500
Morris	1,300,000	325,000	975,000
Nacogdoches	4,500,000	1,125,000	3,375,000
Robertson	8,800,000	2,200,000	6,600,000
Rusk	58,000	14,500	43,500
Smith	23,000,000	5,750,000	17,250,000
Titus	63,000	15,750	47,250
Trinity	1,900,000	475,000	1,425,000
Upshur	7,800,000	1,950,000	5,850,000
Van Zandt	1,200,000	300,000	900,000
Walker	624,000	156,000	468,000
Washington	4,330,000	1,082,500	3,247,500
Wilson	24,000,000	6,000,000	18,000,000
Wood	8,700,000	2,175,000	6,525,000
Total	**539,257,800**	**134,814,450**	**404,443,350**

Water quality

Groundwater in the Queen City Aquifer is generally fresh, with an average of about 300 milligrams per liter total dissolved solids in the recharge zone and about 750 milligrams per liter deeper in the aquifer (Figure 6-89). Although salinity decreases from south to north, areas of excessive iron concentration and high acidity occur in the northeast.

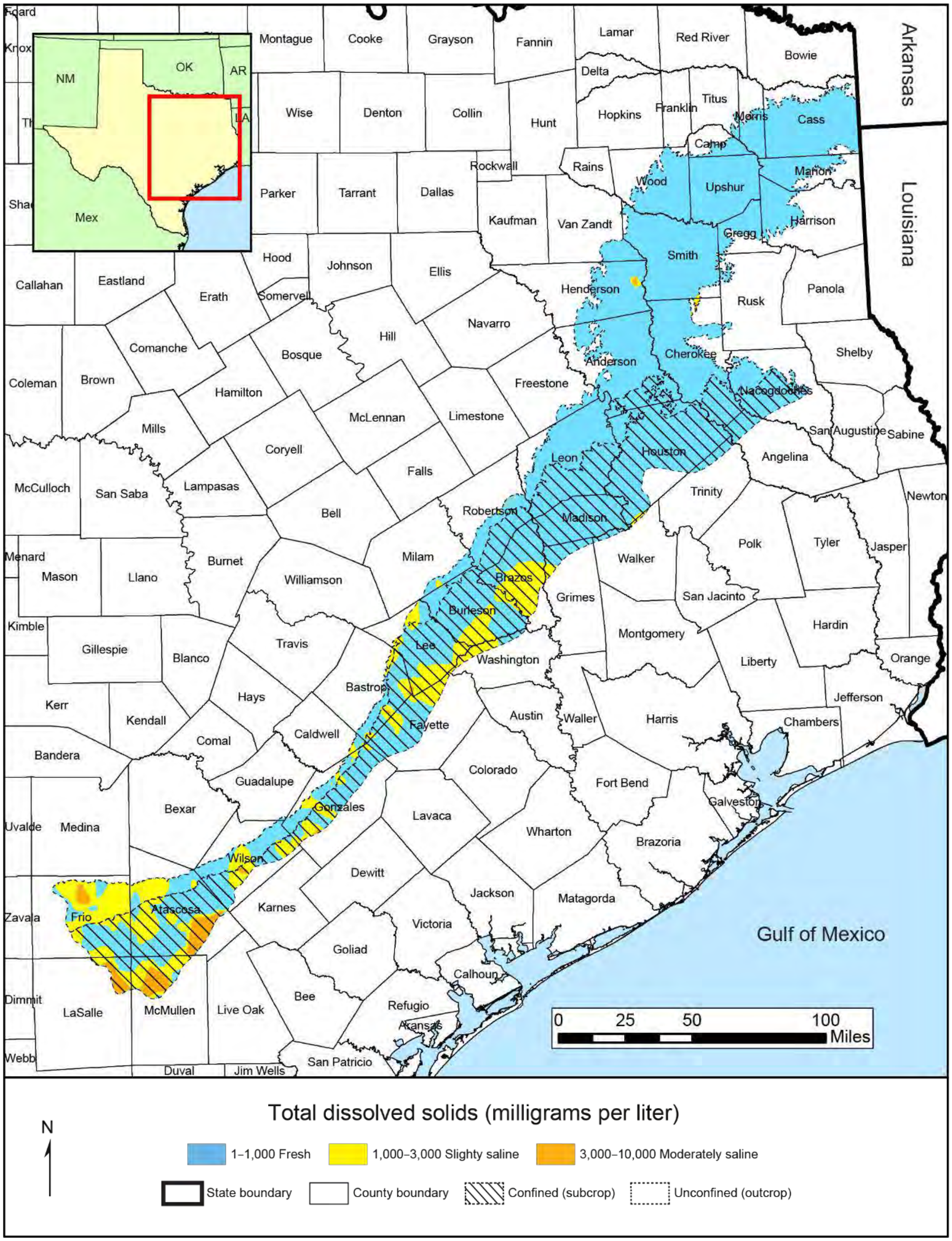


Figure 6-89. **Total dissolved solids in the Queen City Aquifer.**

6.25 Rita Blanca Aquifer

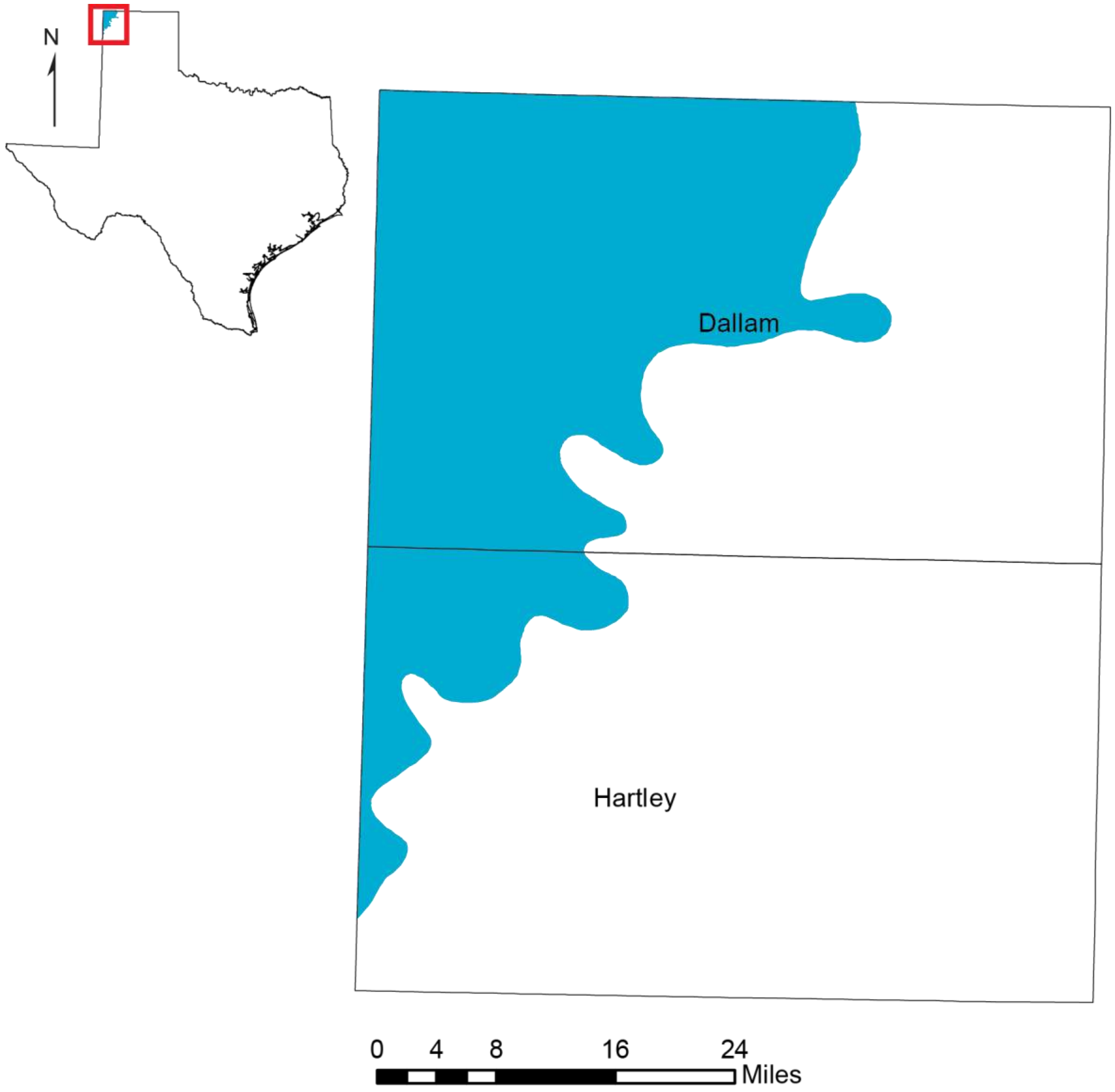


Figure 6-90. Extent of the Rita Blanca Aquifer.

Aquifer characteristics

- Aquifer type: mostly confined
- Area of aquifer: 918 square miles
- Proportion of aquifer with groundwater conservation districts: 99 percent
- Number of counties containing the aquifer: 2

Geology and hydrogeology

The Rita Blanca Aquifer is a minor aquifer that underlies the Ogallala Aquifer in the northwest corner of the Texas Panhandle (Figure 6-90) and extends into New Mexico and Oklahoma. Groundwater occurs in the coarse-grained sand and gravel layers of the Lytle and Dakota formations, as well as in the Exeter Sandstone and the Morrison Formation (Figure 6-91). The thickness of the aquifer is as much as 250 feet, and freshwater saturated thickness averages about 180 feet. Groundwater in the Rita Blanca Aquifer is generally under confined conditions in Texas. In some places, the Rita Blanca Aquifer is hydraulically connected to the Ogallala Aquifer and the underlying Dockum Aquifer. The total thickness of water-bearing rocks in these places is much greater.

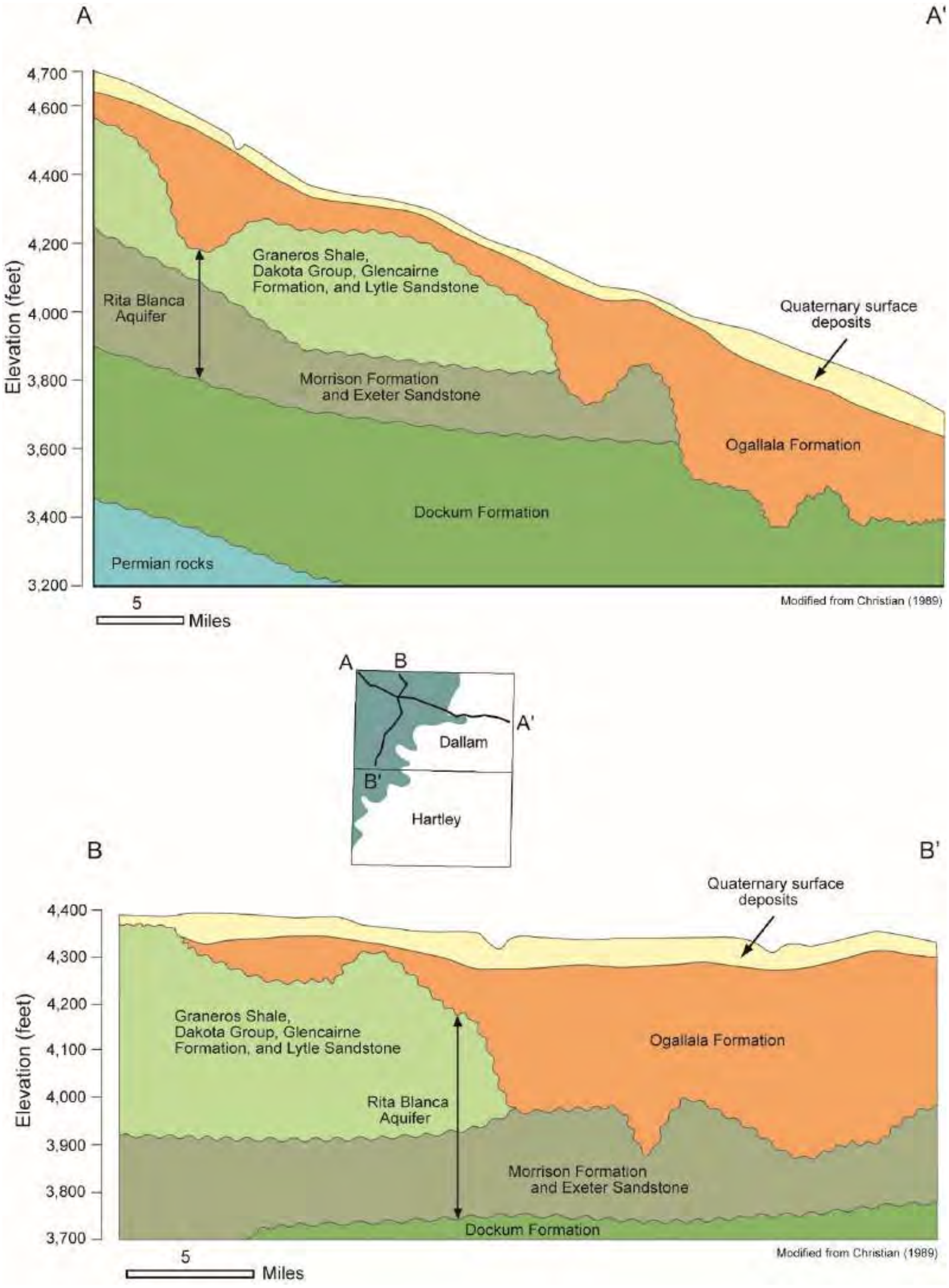


Figure 6-91. Geologic cross-section of the Rita Blanca Aquifer (modified from Christian, 1989).

Flows to surface water and other aquifers

The Rita Blanca Aquifer does not have any outcrop area in Texas and consequently there is no direct flow between the Rita Blanca Aquifer and surface-water bodies. Table 6-66 shows groundwater availability model estimates of total flow and average annual flow between the Rita Blanca Aquifer and other aquifers.

Table 6-66. Model estimates of inter-aquifer flows between the Rita Blanca Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Rita Blanca Aquifer	Dockum Aquifer	83
Dockum Aquifer	Rita Blanca Aquifer	115
Ogallala Aquifer	Rita Blanca Aquifer	1,670

Water quantity

Total storage in the Rita Blanca Aquifer is estimated to be about 11.1 million acre-feet. Recoverable storage is estimated to be between 25 and 75 of the total, about 2.7 million to 8.3 million acre-feet (Table 6-67).

Table 6-67. Total estimated recoverable storage in the Rita Blanca Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Dallam	9,800,000	2,450,000	7,350,000
Hartley	1,300,000	325,000	975,000
Total	**11,100,000**	**2,775,000**	**8,325,000**

Water quality

Water in the Rita Blanca Aquifer is usually fresh, containing less than 1,000 milligrams per liter of total dissolved solids, but very hard; however, some parts of the aquifer produce water that is slightly saline, containing more than 1,000 milligrams per liter of total dissolved solids (Figure 6-92). Primary and secondary maximum contaminant level exceedances for gross alpha radiation, arsenic, fluoride, and total dissolved solids occur in a small percentage of wells completed in the Rita Blanca (Reedy and others, 2011).

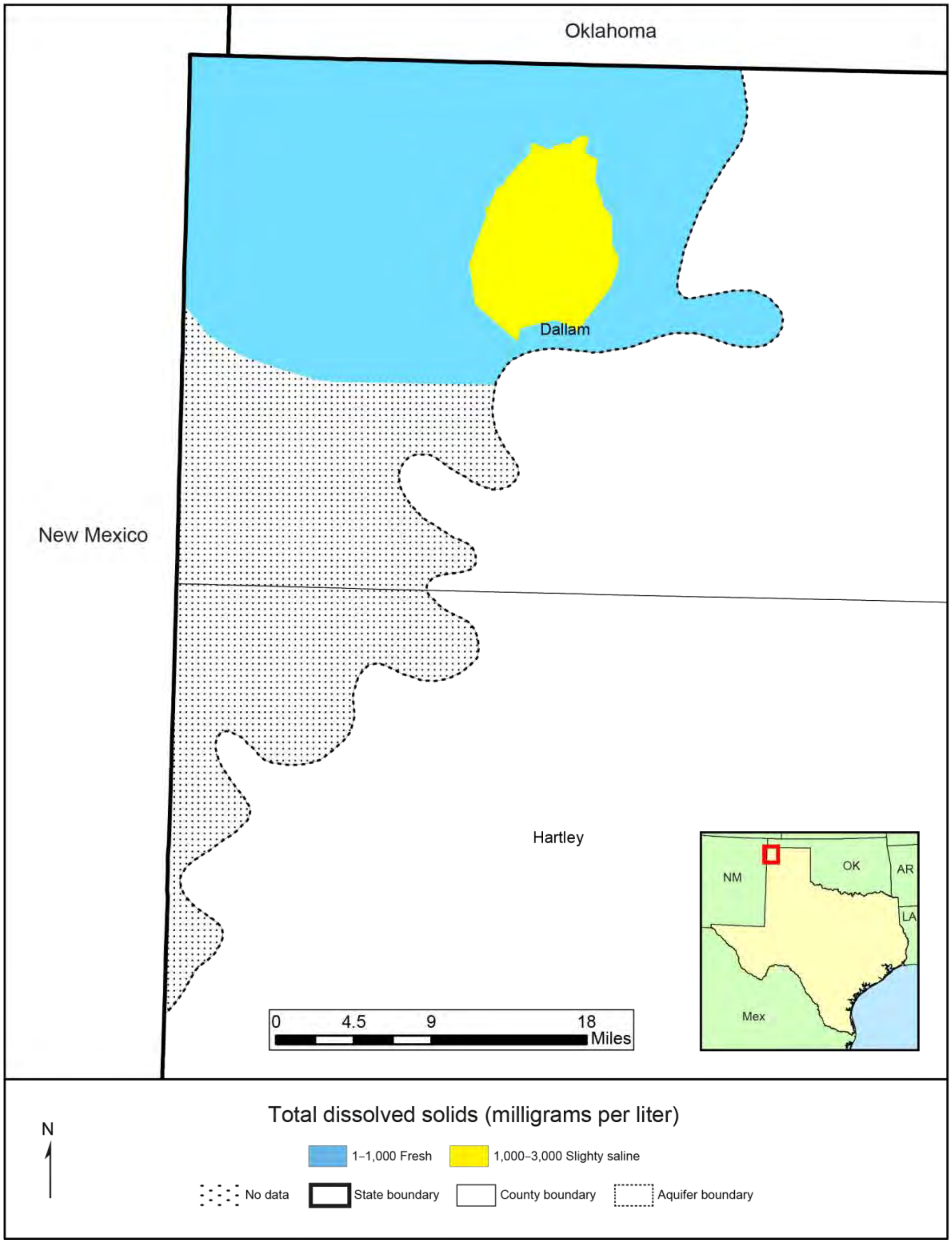


Figure 6-92. Total dissolved solids in the Rita Blanca Aquifer.

6.26 Rustler Aquifer

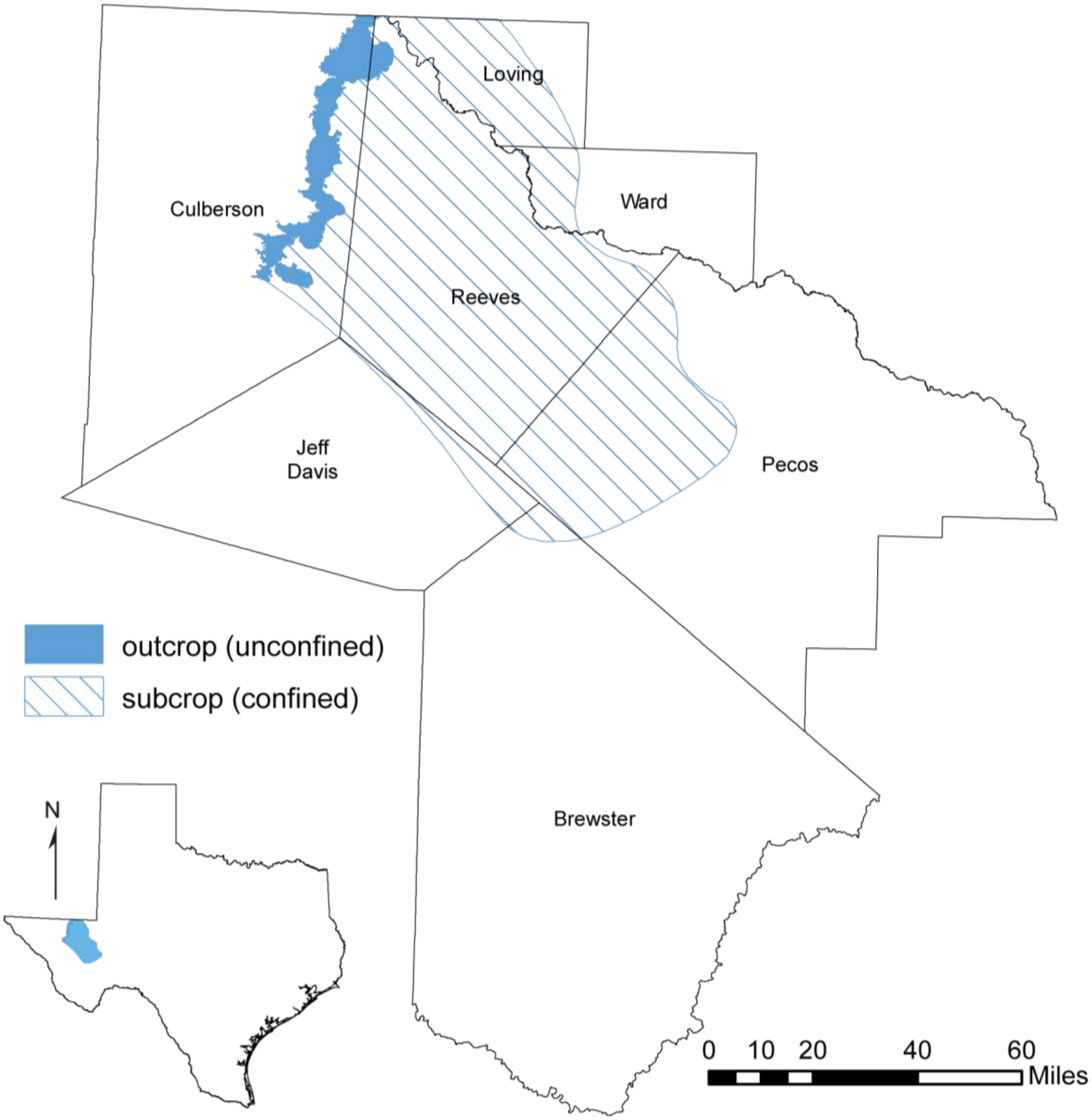


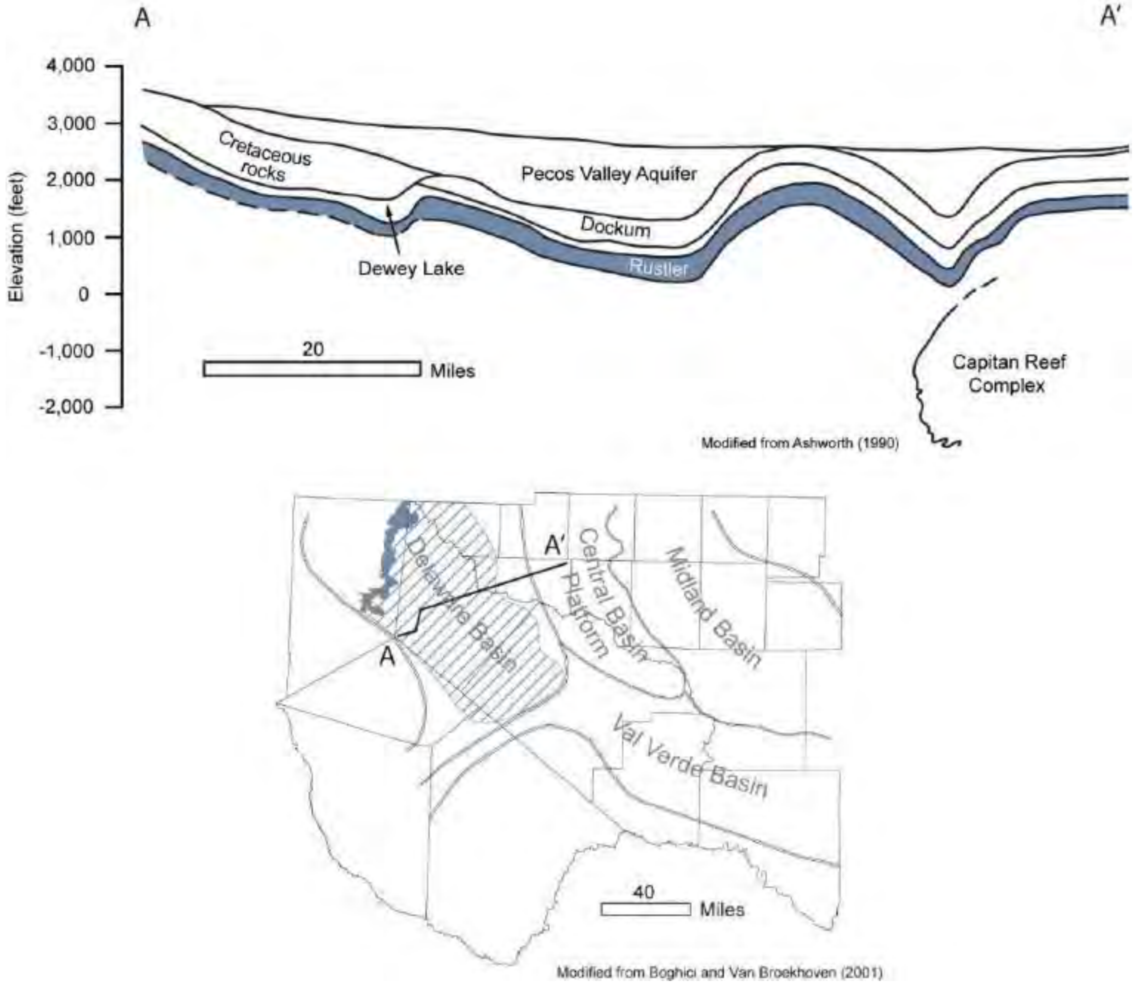
Figure 6-93. Extent of the Rustler Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 311 square miles
- Area in subsurface: 4,881 square miles
- Proportion of aquifer with groundwater conservation districts: 76 percent
- Number of counties containing the aquifer: 7

Geology and hydrogeology

The Rustler Aquifer is a minor aquifer located in Brewster, Culberson, Jeff Davis, Loving, Pecos, Reeves, and Ward counties (Figure 6-93). The aquifer consists of the carbonates and evaporites of the Rustler Formation, which is the youngest unit of the Late Permian Ochoan Series. The Rustler Formation is 250 to 670 feet thick and extends down-dip into the subsurface toward the center of the Delaware Basin to the east (Figure 6-94). It becomes thinner along the eastern margin of the Delaware Basin and across the Central Basin Platform and Val Verde Basin. There it conformably overlies the Salado Formation. Groundwater occurs in partly dissolved dolomite, limestone, and gypsum. Most of the water production comes from fractures and solution openings in the upper part of the formation.



Modified from Ashworth (1990)

Modified from Boghici and Van Broekhoven (2001)

Figure 6-94. **Geologic cross-section of the Rustler Aquifer. The index map shows the major structures in the region (modified from Ashworth, 1990; Boghici and Van Broekhoven, 2001).**

Flows to surface water and other aquifers

The Rustler Aquifer only in outcrops in Culberson and Reeves Counties and has limited discharge to surface water in the area. Results of the baseflow analysis for the Rustler Aquifer are shown in Table 6-68. Table 6-69 shows groundwater availability model estimates of total flow and average annual flow between the Rustler Aquifer and other aquifers.

Table 6-68. Summary of groundwater flow from the Rustler Aquifer to surface water.

County	Area of aquifer Outcrop in county (square miles)	Sum of average Annual baseflow (cubic feet per second)	Sum of median Annual baseflow (cubic feet per second)
Culberson	289	1.9	0.7
Reeves	24	0.1	0
Total	**313**	**2**	**0.7**

Table 6-69. Model estimates of inter-aquifer flows between the Rustler and Dockum aquifers.

Flow from	Flow to	Total flow (acre-feet per year)	Average annual (net, acre-feet)
Rustler Aquifer	Dockum Aquifer	1	1

Water quantity

Total storage in the Rustler Aquifer is estimated to be nearly 37 million acre-feet. Recoverable storage is estimated to be between 25 and 75 of the total, or about 9.2 million to 27.6 million acre-feet (Table 6-70).

Table 6-70. Total estimated recoverable storage in the Rustler Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Brewster	53,000	13,250	39,750
Culberson	4,200,000	1,050,000	3,150,000
Jeff Davis	670,000	167,500	502,500
Loving	3,400,000	850,000	2,550,000
Pecos	8,600,000	2,150,000	6,450,000
Reeves	19,000,000	4,750,000	14,250,000
Ward	980,000	245,000	735,000
Total	**36,903,000**	**9,225,750**	**27,677,250**

Water quality

Although some parts of the aquifer produce freshwater containing less than 1,000 milligrams per liter of total dissolved solids, the water is generally slightly to moderately saline and contains total dissolved solids between 1,000 and 4,600 milligrams per liter (Figure 6-95).

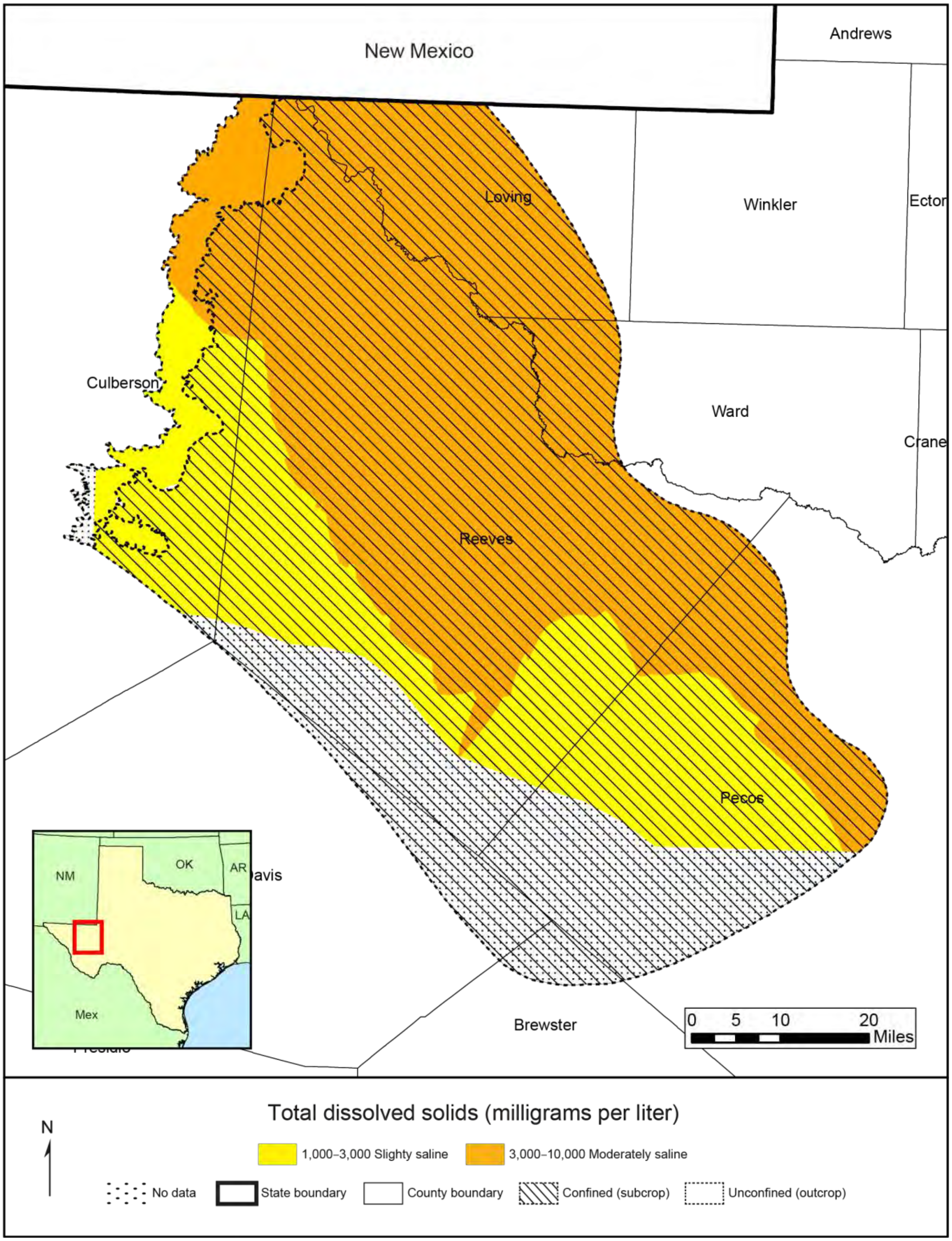


Figure 6-95. Total dissolved solids in the Rustler Aquifer.

6.27 Sparta Aquifer

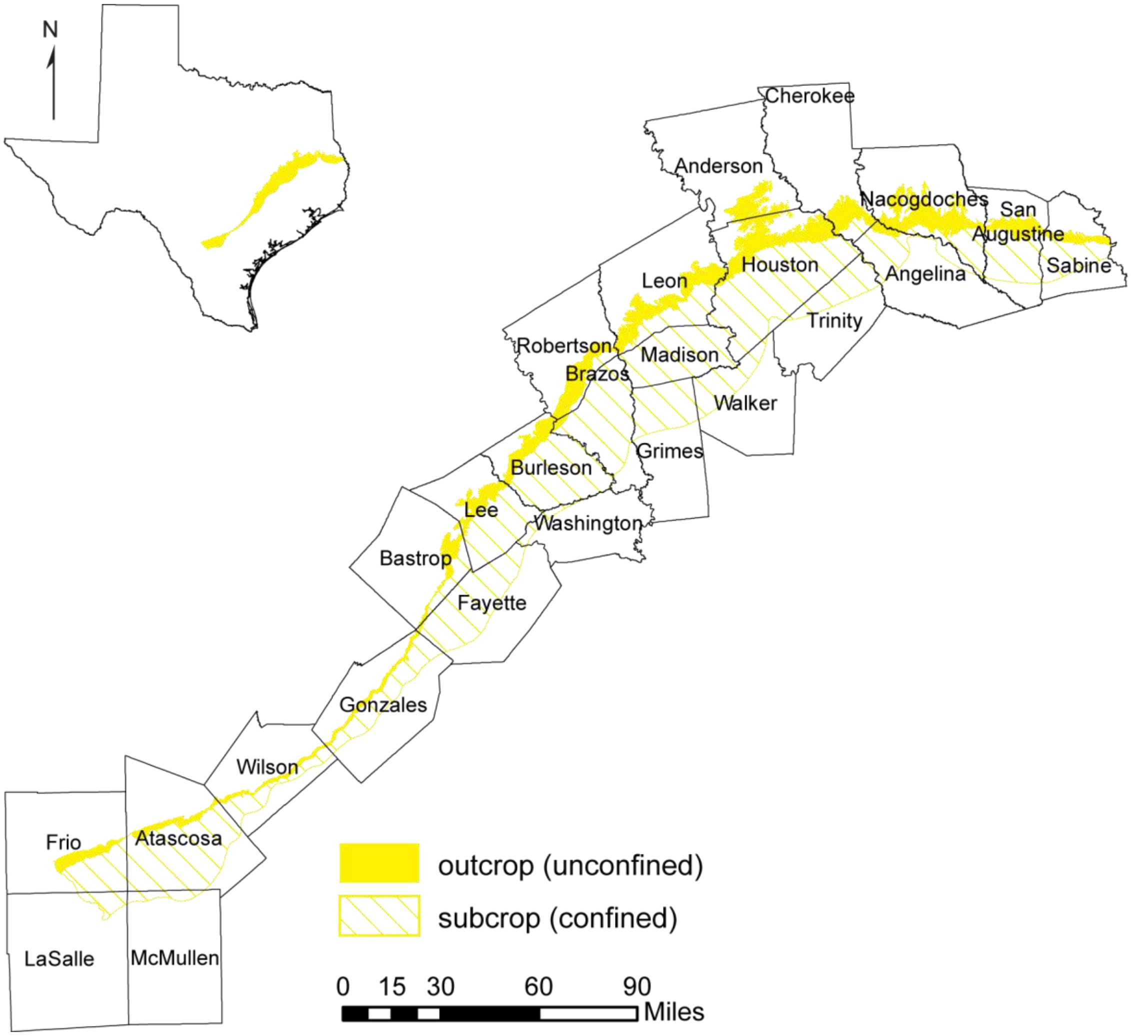


Figure 6-96. Extent of the Sparta Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 1,549 square miles
- Area in subsurface: 6,321 square miles
- Proportion of aquifer with groundwater conservation districts: 76 percent
- Number of counties containing the aquifer: 25

Geology and hydrogeology

The Sparta Aquifer is a minor aquifer extending across east and south Texas, parallel to the Gulf of Mexico coastline and about 100 miles inland (Figure 6-96). Water is contained within a part of the Claiborne Group known as the Sparta Formation, a sand-rich unit interbedded with silt and clay layers and with massive sand beds in the bottom section. The thickness of the formation changes gradually from more than 700 feet at the Sabine River to about 200 feet in south Texas. Freshwater saturated thickness averages about 120 feet (Figure 6-97).

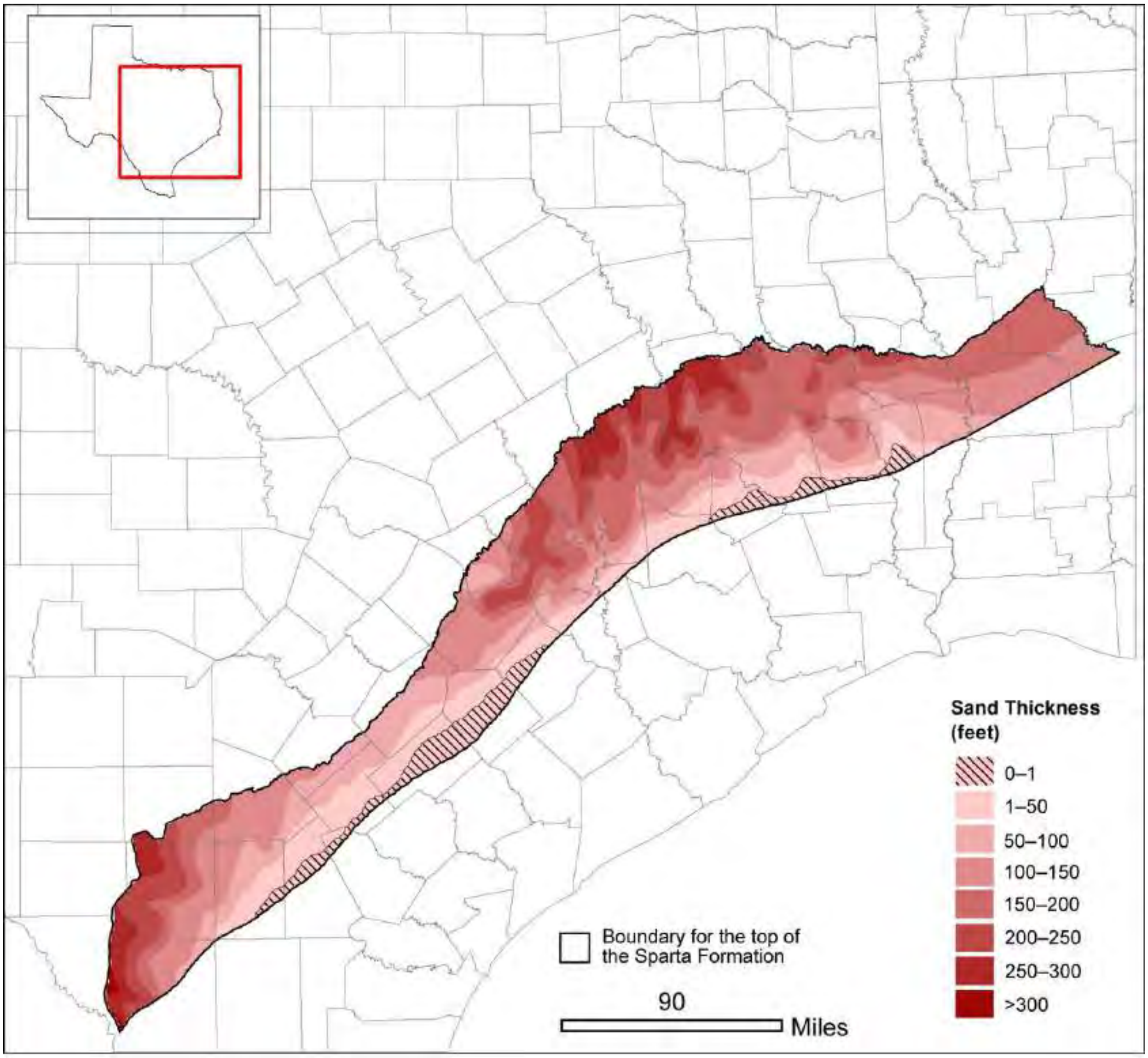


Figure 6-97. Total sand thickness in the Sparta Aquifer (modified from Ricoy and Brown, 1977; Kelley and others, 2004).

Flows to surface water and other aquifers

Groundwater from the Sparta Aquifer discharges to streams, springs, and other formations. Table 6-71 shows a summary of baseflow in the outcrop areas of the Sparta Aquifer. Groundwater availability model analysis does not estimate any inter-aquifer flow between the Sparta Aquifer and other major and minor aquifers.

Table 6-71. Summary of groundwater flow from the Sparta Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Anderson	94	20.2	6.4
Angelina	20	6.4	2.2
Atascosa	49	3.3	1.2
Bastrop	62	3.1	0.8
Burleson	83	4.7	0.7
Cherokee	86	27.3	10.3
Fayette	3	0.3	0.1
Frio	60	1.3	0.4
Gonzales	47	4.6	1.4
Houston	238	59.8	21.2
Lee	79	3.8	0.6
Leon	202	20.4	4.3
Nacogdoches	223	66.5	17.9
Robertson	105	5.7	0.6
Sabine	47	10.7	2.2
San Augustine	77	20.3	4.9
Wilson	39	3.1	1.1
Total	**1,514**	**262**	**76**

Water quantity

Total storage in the Sparta Aquifer is estimated to be more than 185 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, or about 46.4 million to 139.2 million acre-feet (Table 6-72).

Table 6-72. Total estimated recoverable storage in the Sparta Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Anderson	640,000	160,000	480,000
Angelina	5,200,000	1,300,000	3,900,000
Atascosa	12,000,000	3,000,000	9,000,000
Bastrop	2,500,000	625,000	1,875,000
Brazos	17,000,000	4,250,000	12,750,000
Burleson	16,000,000	4,000,000	12,000,000
Cherokee	1,700,000	425,000	1,275,000
Fayette	14,900,000	3,725,000	11,175,000
Frio	2,600,000	650,000	1,950,000
Gonzales	5,600,000	1,400,000	4,200,000
Grimes	11,600,000	2,900,000	8,700,000
Houston	25,000,000	6,250,000	18,750,000
La Salle	1,600,000	400,000	1,200,000
Lee	10,000,000	2,500,000	7,500,000
Leon	4,600,000	1,150,000	3,450,000
Madison	16,000,000	4,000,000	12,000,000
McMullen	1,700,000	425,000	1,275,000
Nacogdoches	3,900,000	975,000	2,925,000
Robertson	1,300,000	325,000	975,000
Sabine	6,000,000	1,500,000	4,500,000
San Augustine	6,800,000	1,700,000	5,100,000
Trinity	6,100,000	1,525,000	4,575,000
Walker	8,550,000	2,137,500	6,412,500
Washington	1,860,000	465,000	1,395,000
Wilson	2,500,000	625,000	1,875,000
Total	**185,650,000**	**46,412,500**	**139,237,500**

Water quality

In outcrop areas of the Sparta Aquifer and for a few miles down-dip in the subsurface, the water is usually fresh, with an average concentration of 300 milligrams per liter of total dissolved solids. Water quality deteriorates with depth (below about 2,000 feet), where groundwater has an average concentration of 800 milligrams per liter of total dissolved solids (Figure 6-98). Excessive iron concentrations are common throughout the aquifer.

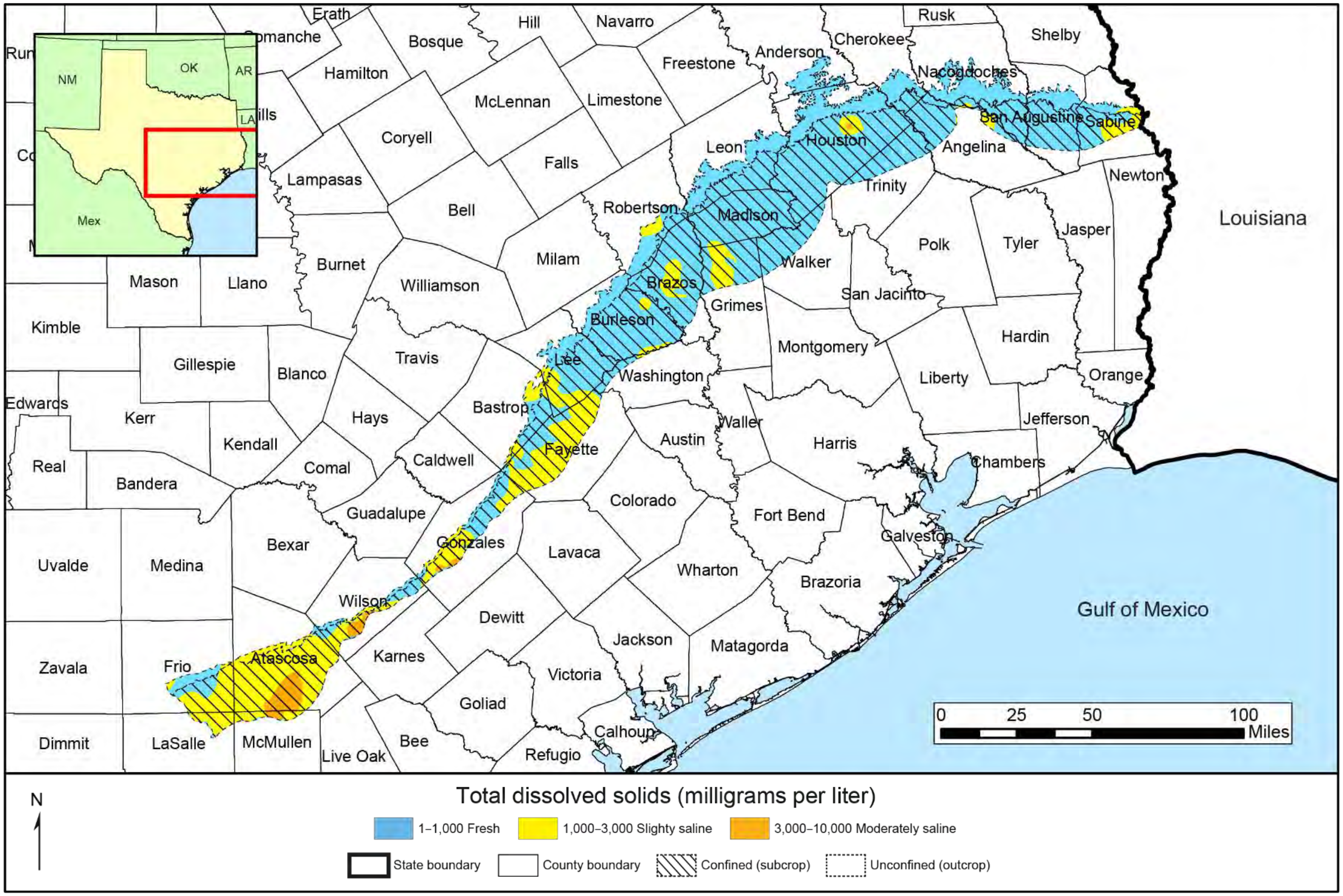


Figure 6-98. **Total dissolved solids in the Sparta Aquifer.**

6.28 West Texas Bolsons Aquifer

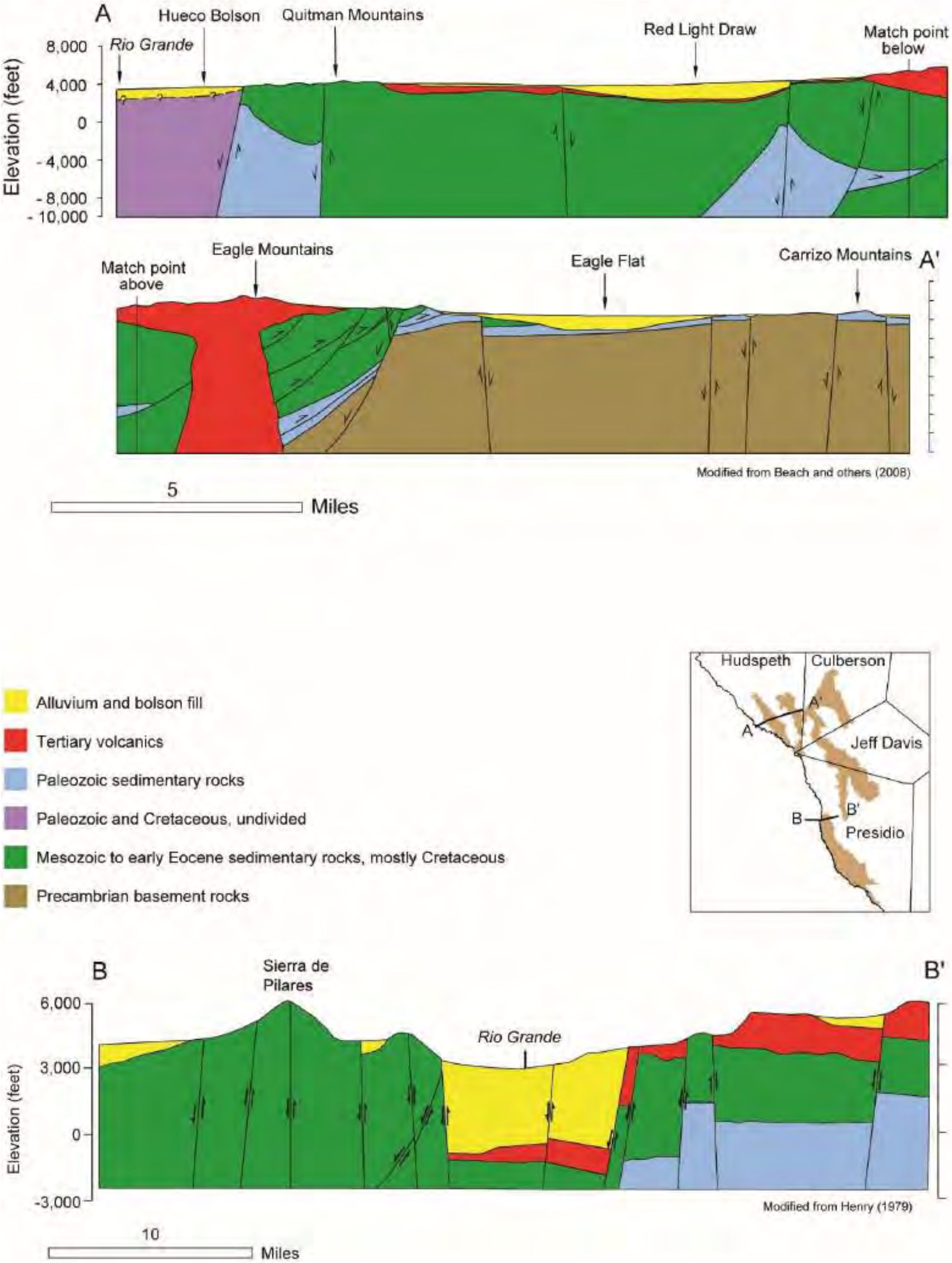
Figure 6-99. Extent of the West Texas Bolsons Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 1,898 square miles
- Proportion of aquifer with groundwater conservation districts: 81 percent
- Number of counties containing the aquifer: 4

Geology and hydrogeology

The West Texas Bolsons Aquifer is a minor aquifer located in several basins, or bolsons, in far west Texas (Figure 6-99). The aquifer occurs as water-bearing, basin-fill deposits as much as 3,000 feet thick. It is composed of eroded materials that vary depending on the mountains bordering the basins and the manner in which the sediments were deposited. Sediments range from the fine-grained silt and clay of lake deposits to the coarse-grained volcanic rock and limestone of alluvial fans (Figure 6-100). Freshwater saturated thickness averages about 580 feet.



Modified from Beach and others (2008)

Modified from Henry (1979)

Figure 6-100. Structural cross-section across the northern West Texas Bolsons Aquifer, *above* (modified from Beach and others, 2008) and the southern Presidio Bolson, *below* (modified from Henry, 1979).

Flows to surface water and other aquifers

The Presidio and Redford bolsons discharge through springs, evapotranspiration, baseflow, and groundwater pumping. Springs include hot, thermal springs, representing deep groundwater circulation and cold springs, resulting from shallow groundwater discharge (Wade and others, 2011). Table 6-73 shows a summary of baseflow in the outcrop areas of the West Texas Bolsons Aquifer. Groundwater availability model analysis does not estimate any inter-aquifer flow between the West Texas Bolsons Aquifer and other major and minor aquifers.

Table 6-73. Summary of groundwater flow from the West Texas Bolsons Aquifer to surface water.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Culberson	450	1.8	1.7
Hudspeth	353	1	1.3
Jeff Davis	248	0.7	1
Presidio	793	2.1	3
Total	**1,844**	**6**	**7**

Water quantity

Total storage in the West Texas Bolsons Aquifer is estimated to be more than 51 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, or about 12.8 million to 38.5 million acre-feet (Table 6-74). Water levels in the West Texas Bolsons Aquifer have been declining since the 1950s, with the most significant declines occurring south of Van Horn in the Lobo Flats area and to the east in the Wild Horse Basin area.

Table 6-74. Total estimated recoverable storage in the West Texas Bolsons Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Culberson	5,400,000	1,350,000	4,050,000
Hudspeth	6,800,000	1,700,000	5,100,000
Jeff Davis	4,200,000	1,050,000	3,150,000
Presidio	35,000,000	8,750,000	26,250,000
Total	**51,400,000**	**12,850,000**	**38,550,000**

Water quality

Groundwater quality varies depending on the basin, ranging from freshwater, containing less than 1,000 milligrams per liter of total dissolved solids, to slightly to moderately saline water, containing between 1,000 and 4,000 milligrams per liter of total dissolved solids (Figure 6-101). Groundwater in the central and southern regions of the aquifer commonly exceeds maximum contaminant level for arsenic, fluoride, gross alpha radiation, or nitrate-N. The northern regions of the aquifer are more likely to exceed the maximum contaminant level for total dissolved solids. (Reedy and others, 2011).

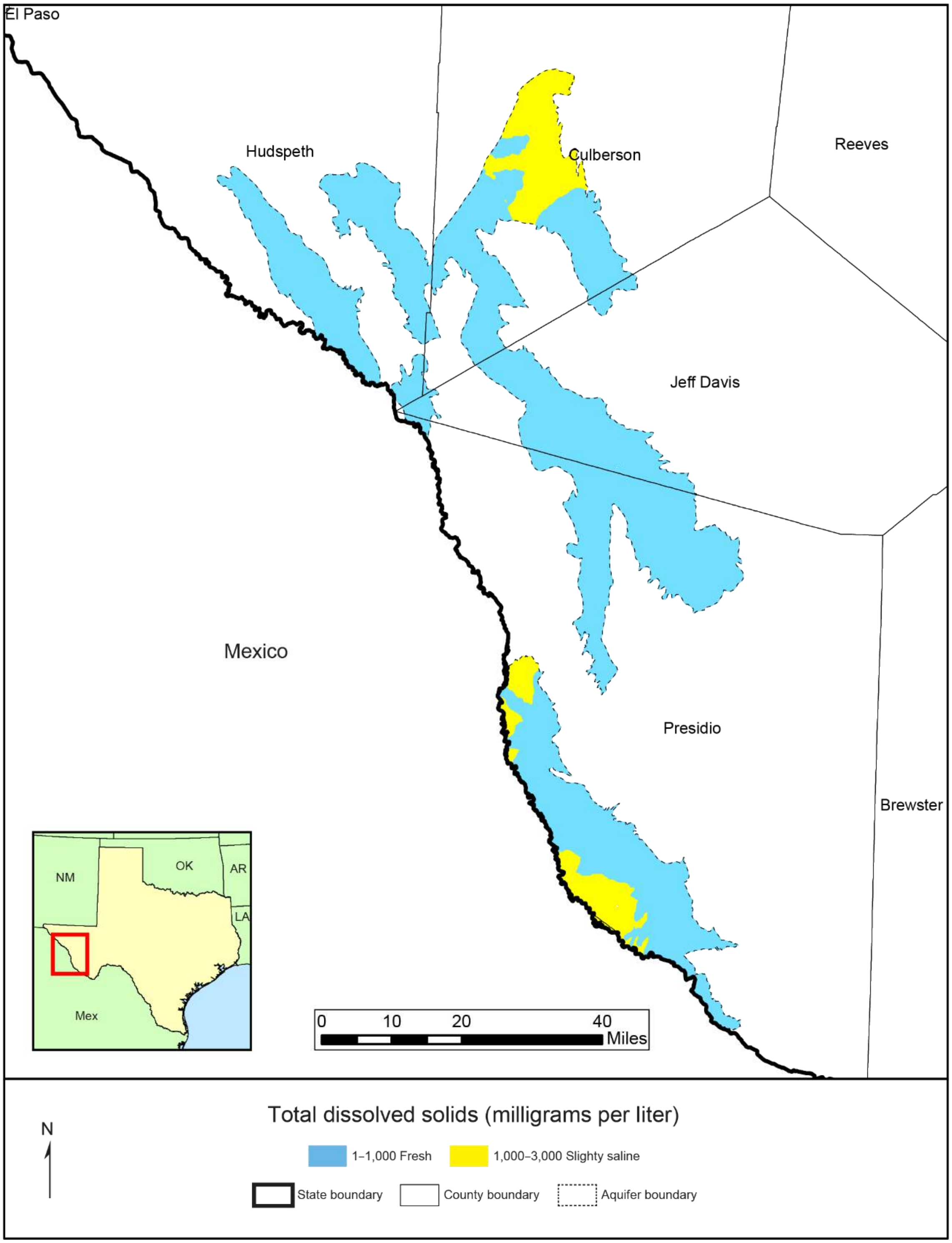


Figure 6-101. Total dissolved solids in the West Texas Bolsons Aquifer.

6.29 Woodbine Aquifer

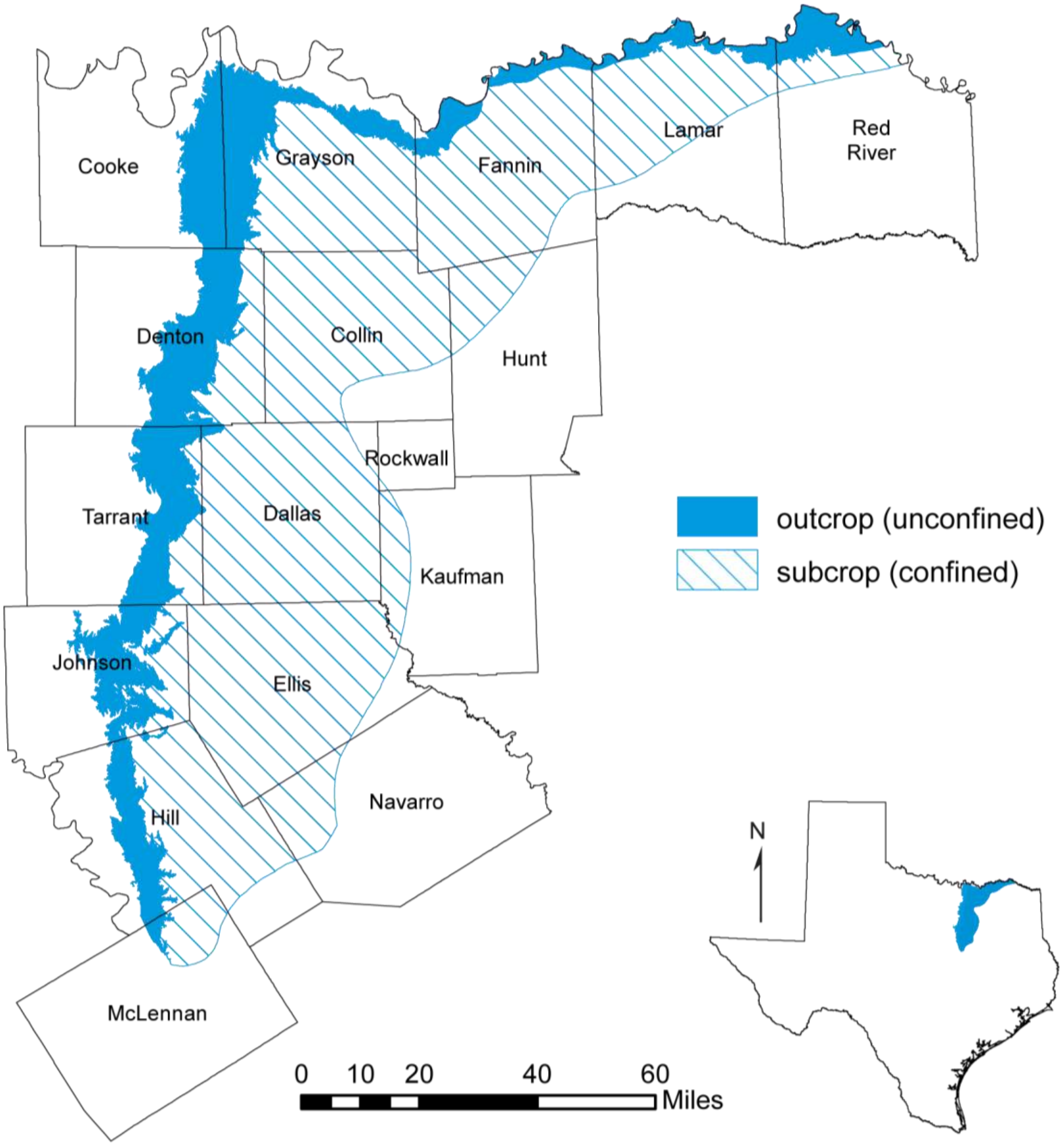


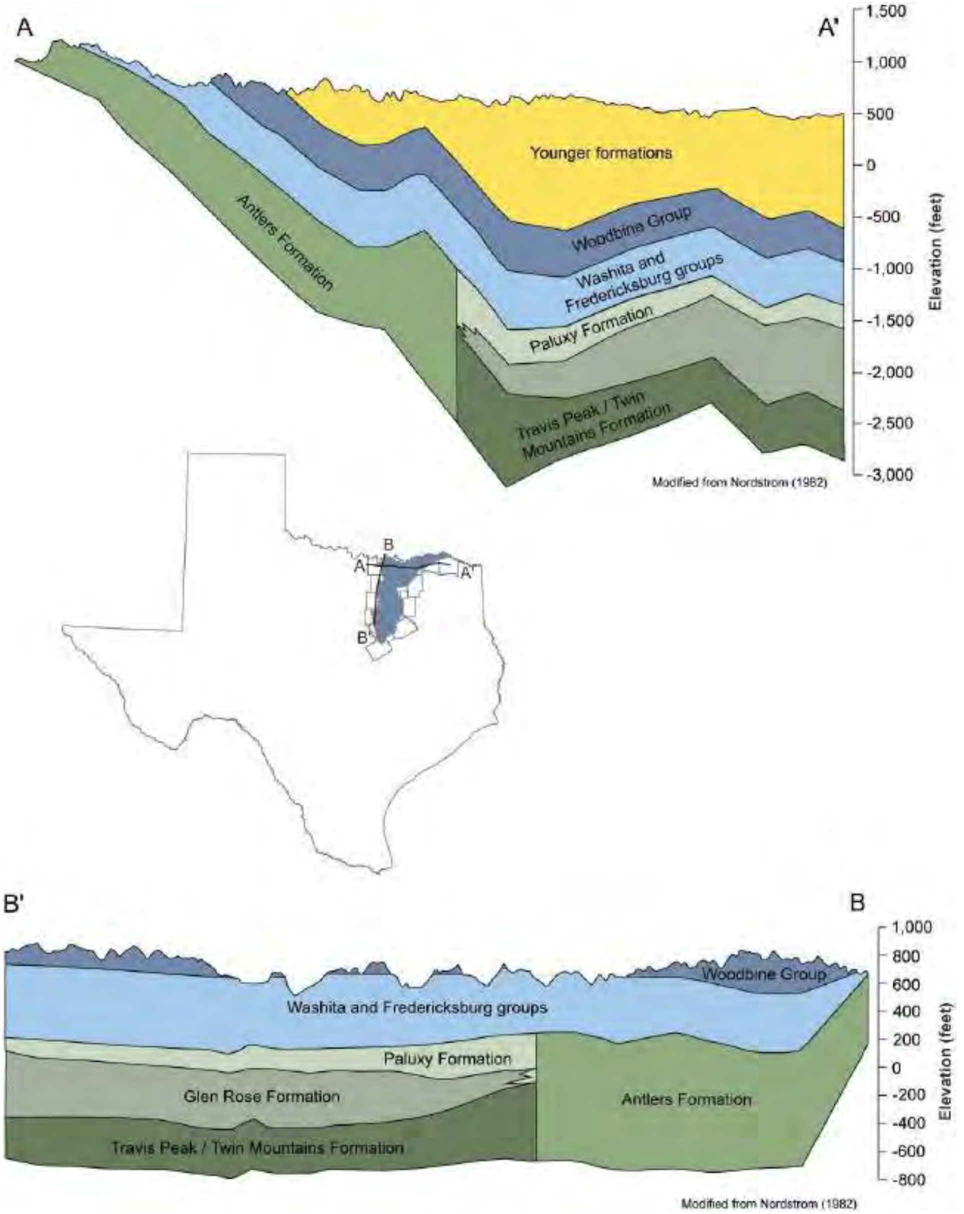
Figure 6-102. Extent of the Woodbine Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 1,561 square miles
- Area of subsurface: 5,784 square miles
- Proportion of aquifer with groundwater conservation districts: 73 percent
- Number of counties containing the aquifer: 17

Geology and hydrogeology

The Woodbine Aquifer is a minor aquifer located in northeast Texas (Figure 6-102). The aquifer overlies the Trinity Aquifer and consists of sandstone interbedded with shale and clay that form three distinct water-bearing zones (Figure 6-103). The Woodbine Aquifer reaches 600 feet in thickness in subsurface areas, and freshwater saturated thickness averages about 160 feet. Water yield varies with the depth of the aquifer. The lower zones of the aquifer typically yield the most water while the upper zone yields limited water.



Modified from Nordstrom (1982)

Modified from Nordstrom (1982)

Figure 6-103. Structural cross-sections along and across Woodbine Group rocks (modified from Nordstrom, 1982).

Flows to surface water and other aquifers

Reservoirs and streams intersect the Woodbine Aquifer outcrop area. There are also springs in the area that originate in the Woodbine Aquifer (Intera, 2014). Table 6-75 summarizes baseflow in the outcrop areas of the Woodbine Aquifer. Groundwater availability model analysis does not estimate any inter-aquifer flow between the Woodbine Aquifer and other major and minor aquifers.

Table 6-75. Summary of groundwater flow from the Woodbine Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Cooke	178	10.4	1.1
Dallas	7	0.6	0.1
Denton	272	19.7	2.4
Fannin	93	9.2	2.1
Grayson	267	13.9	2
Hill	149	8.1	0.6
Johnson	191	8.5	0.6
Lamar	70	10.8	2.3
McLennan	12	0.7	0
Red River	88	9.4	0.7
Tarrant	232	10.6	1.6
Total	**1,559**	**102**	**14**

Water quantity

Total storage in the Woodbine Aquifer is estimated to be more than 227 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, or about 56.8 million to 170.5 million acre-feet (Table 6-76).

Table 6-76. Total estimated recoverable storage in the Woodbine Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Collin	32,000,000	8,000,000	24,000,000
Cooke	1,200,000	300,000	900,000
Dallas	30,000,000	7,500,000	22,500,000
Denton	8,900,000	2,225,000	6,675,000
Ellis	25,000,000	6,250,000	18,750,000
Fannin	39,000,000	9,750,000	29,250,000
Grayson	32,000,000	8,000,000	24,000,000
Hill	6,700,000	1,675,000	5,025,000
Hunt	8,200,000	2,050,000	6,150,000
Johnson	4,500,000	1,125,000	3,375,000
Kaufman	4,700,000	1,175,000	3,525,000
Lamar	21,000,000	5,250,000	15,750,000
McLennan	900,000	225,000	675,000
Navarro	3,400,000	850,000	2,550,000
Red River	4,500,000	1,125,000	3,375,000
Rockwall	46,000	11,500	34,500
Tarrant	5,300,000	1,325,000	3,975,000
Total	**227,346,000**	**56,836,500**	**170,509,500**

Water quality

Water quality varies with the depth of the aquifer. The upper zone tends to be very high in iron. In general, water to a depth of 1,500 feet is fresh, containing less than 1,000 milligrams per liter of total dissolved solids. Water at depths below 1,500 feet is slightly to moderately saline, containing from 1,000 to 4,000 milligrams per liter of total dissolved solids (Figure 6-104). The groundwater exceeds the maximum contaminant level for fluoride in a small percentage of wells completed in the Woodbine Aquifer (Reedy and others, 2011).

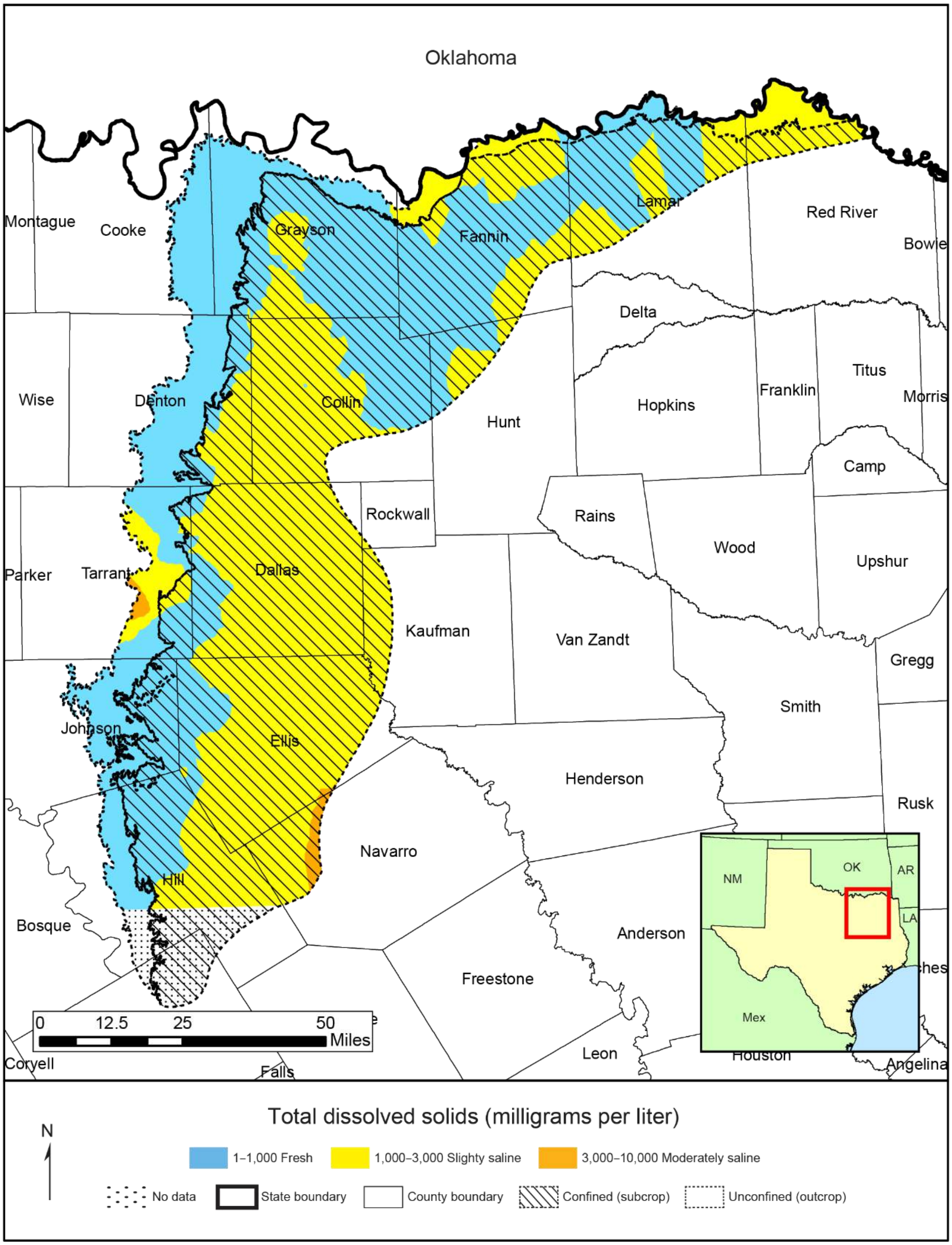


Figure 6-104. Total dissolved solids in the Woodbine Aquifer.

6.30 Yegua-Jackson Aquifer

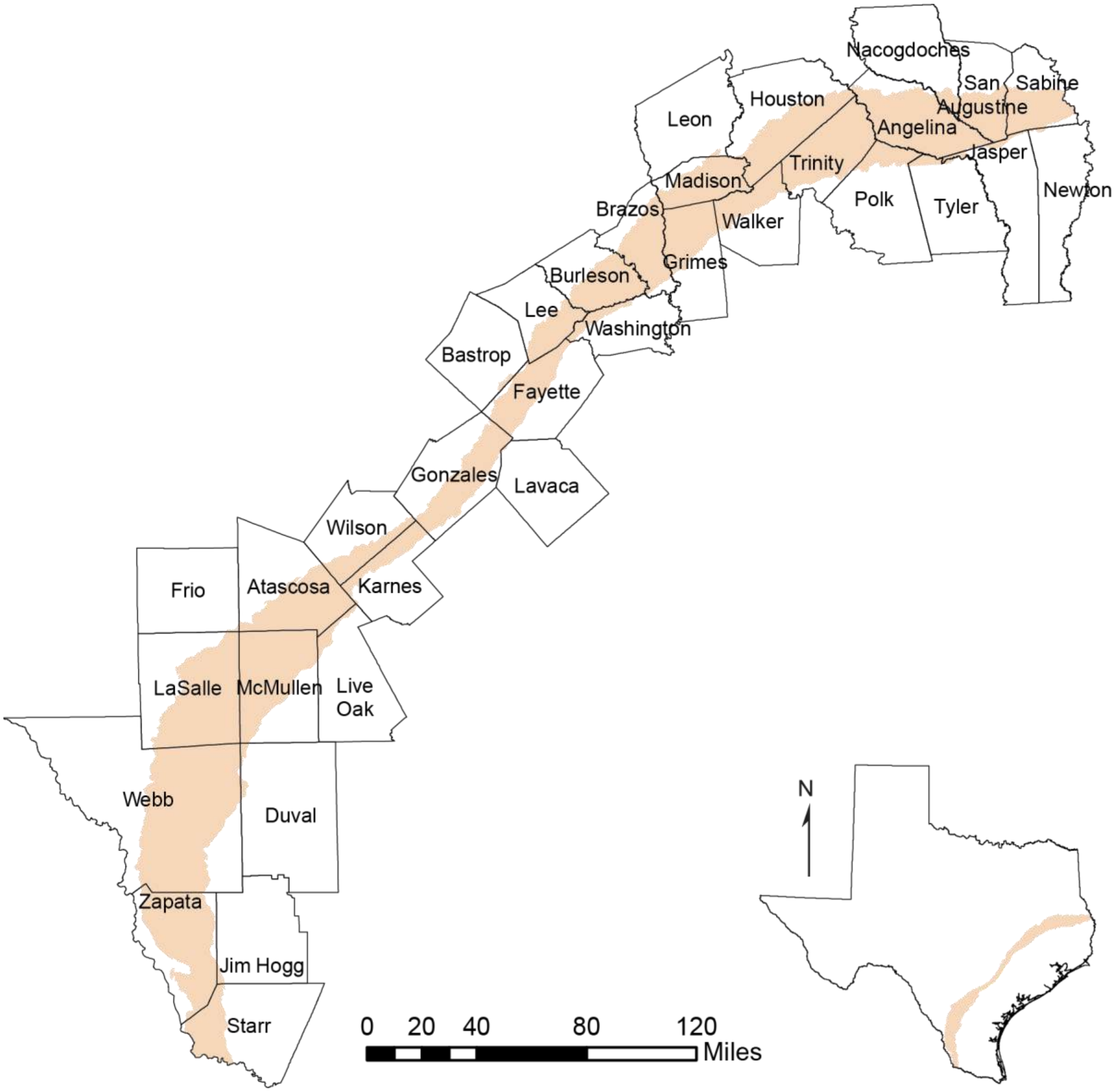


Figure 6-105. Extent of the Yegua-Jackson Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 10,932 square miles
- Proportion of aquifer with groundwater conservation districts: 62 percent
- Number of counties containing the aquifer: 34

Geology and hydrogeology

The Yegua-Jackson Aquifer is a minor aquifer stretching across the southeast part of the state (Figure 6-105). It includes water-bearing parts of the Yegua Formation (part of the upper Claiborne Group) and the Jackson Group (comprising the Whitsett, Manning, Wellborn, and Caddell formations). These geologic units consist of interbedded sand, silt, and clay layers originally deposited as fluvial and deltaic sediments (Figure 6-106). Freshwater saturated thickness averages about 170 feet.

The Yegua and Jackson formations continue toward the Gulf of Mexico beyond the official boundaries of the Yegua-Jackson Aquifer, but most wells completed in the aquifer are in the outcrop area. Sand-rich intervals form the high-conductivity framework of the aquifer. Sand-rich intervals occur over most of the outcrop area of the aquifer, but down-dip there are broadly distributed areas where sand is absent, limiting groundwater productivity (Deeds and others, 2010).

Flows to surface water and other aquifers

Many rivers and streams intersect the Yegua-Jackson Aquifer outcrop. Previous studies indicate that the aquifer contributes to river and streamflow (Deeds and others, 2010). Table 6-77 shows a summary of baseflow in the outcrop areas of the Yegua-Jackson Aquifer. Groundwater availability model analysis does not estimate any inter-aquifer flow between the Yegua-Jackson Aquifer and other major and minor aquifers.

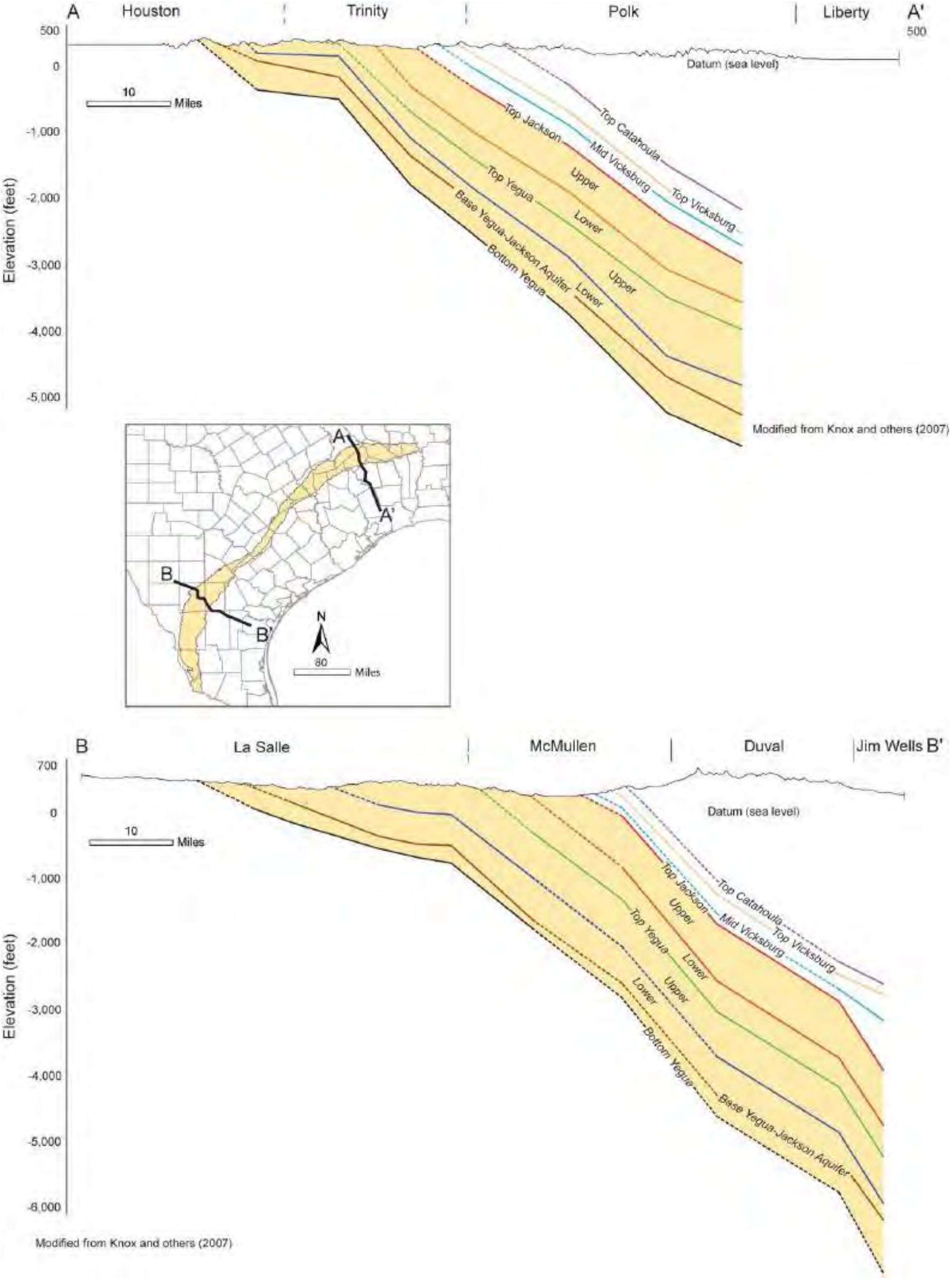


Figure 6-106. Structural cross-sections across the Yegua-Jackson Aquifer (modified from Knox and others, 2007).

Table 6-77. Summary of groundwater flow from the Yegua-Jackson Aquifer to surface water.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Angelina	739	215	68.7
Atascosa	565	29.5	10.7
Bastrop	14	0.6	0.1
Brazos	351	22.6	3.2
Burleson	258	13.9	1.5
Duval	29	0.2	0
Fayette	367	23.7	5.7
Frio	6	0.2	0.1
Gonzales	437	38	9.8
Grimes	352	29.7	2.9
Houston	515	102.7	30.1
Jasper	36	11.8	4.2
Jim Hogg	10	0.1	0
Karnes	188	14.3	5.1
La Salle	905	10.4	2.5
Lavaca	1	0.1	0
Lee	227	20.8	3.1
Leon	6	0.6	0.1
Live Oak	56	1.5	0.5
Madison	391	30.4	3.4
McMullen	747	10.4	2.5
Nacogdoches	55	16.8	5
Newton	4	1.2	0.3
Polk	136	38.3	10.3
Sabine	309	85.6	23.9
San Augustine	262	77.5	22.2
Starr	252	7.6	1.2
Trinity	622	103.3	28.4
Tyler	47	14.8	4.9
Walker	249	26.4	3.7
Washington	80	5.6	0.6
Webb	1549	10.5	1.8
Wilson	193	16.5	6.4

Table 6-77 (continued). Summary of groundwater flow from the Yegua-Jackson Aquifer to surface water.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Zapata	757	5.8	1.5
Total	**10,715**	**986**	**264**

Water quantity

Total storage in the Yegua-Jackson Aquifer is estimated to be more than 1 billion acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, or about 300.6 million to 901.8 million acre-feet (Table 6-79).

Table 6-78. Total estimated recoverable storage in the Yegua-Jackson Aquifer by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Angelina	72,000,000	18,000,000	54,000,000
Atascosa	40,000,000	10,000,000	30,000,000
Bastrop	290,000	72,500	217,500
Brazos	30,000,000	7,500,000	22,500,000
Burleson	27,000,000	6,750,000	20,250,000
Duval	7,200,000	1,800,000	5,400,000
Fayette	27,000,000	6,750,000	20,250,000
Frio	75,000	18,750	56,250
Gonzales	32,000,000	8,000,000	24,000,000
Grimes	94,900,000	23,725,000	71,175,000
Houston	21,000,000	5,250,000	15,750,000
Jasper	6,930,000	1,732,500	5,197,500
Jim Hogg	3,000,000	750,000	2,250,000
Karnes	19,190,000	4,797,500	14,392,500
La Salle	56,000,000	14,000,000	42,000,000
Lavaca	620,000	155,000	465,000
Lee	10,000,000	2,500,000	7,500,000
Leon	76,000	19,000	57,000
Live Oak	11,000,000	2,750,000	8,250,000
Madison	15,000,000	3,750,000	11,250,000

Table 6-78 (continued). Total estimated recoverable storage in the Yegua-Jackson Aquifer by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
McMullen	96,000,000	24,000,000	72,000,000
Nacogdoches	1,400,000	350,000	1,050,000
Newton	1,270,000	317,500	952,500
Polk	27,900,000	6,975,000	20,925,000
Sabine	30,000,000	7,500,000	22,500,000
San Augustine	19,000,000	4,750,000	14,250,000
Starr	46,000,000	11,500,000	34,500,000
Trinity	83,000,000	20,750,000	62,250,000
Tyler	8,650,000	2,162,500	6,487,500
Walker	103,000,000	25,750,000	77,250,000
Washington	12,400,000	3,100,000	9,300,000
Webb	210,820,000	52,705,000	158,115,000
Wilson	6,800,000	1,700,000	5,100,000
Zapata	83,000,000	20,750,000	62,250,000
Total	**1,202,521,000**	**300,630,250**	**901,890,750**

Water quality

Water quality varies greatly due to sediment composition in the aquifer formations, and in all areas the aquifer becomes highly mineralized with depth. Most groundwater is produced from the sand units of the aquifer, where the water is fresh and ranges from less than 50 to 1,000 milligrams per liter of total dissolved solids. Some slightly to moderately saline water, with concentrations of total dissolved solids ranging from 1,000 to 10,000 milligrams per liter, also occurs in the aquifer (Figure 6-107). There is low probability for maximum contaminant level exceedances in the aquifer. However, the southern part of the aquifer tends to have moderate levels of total dissolved solids, iron, and manganese exceedances (Reedy and others, 2011).

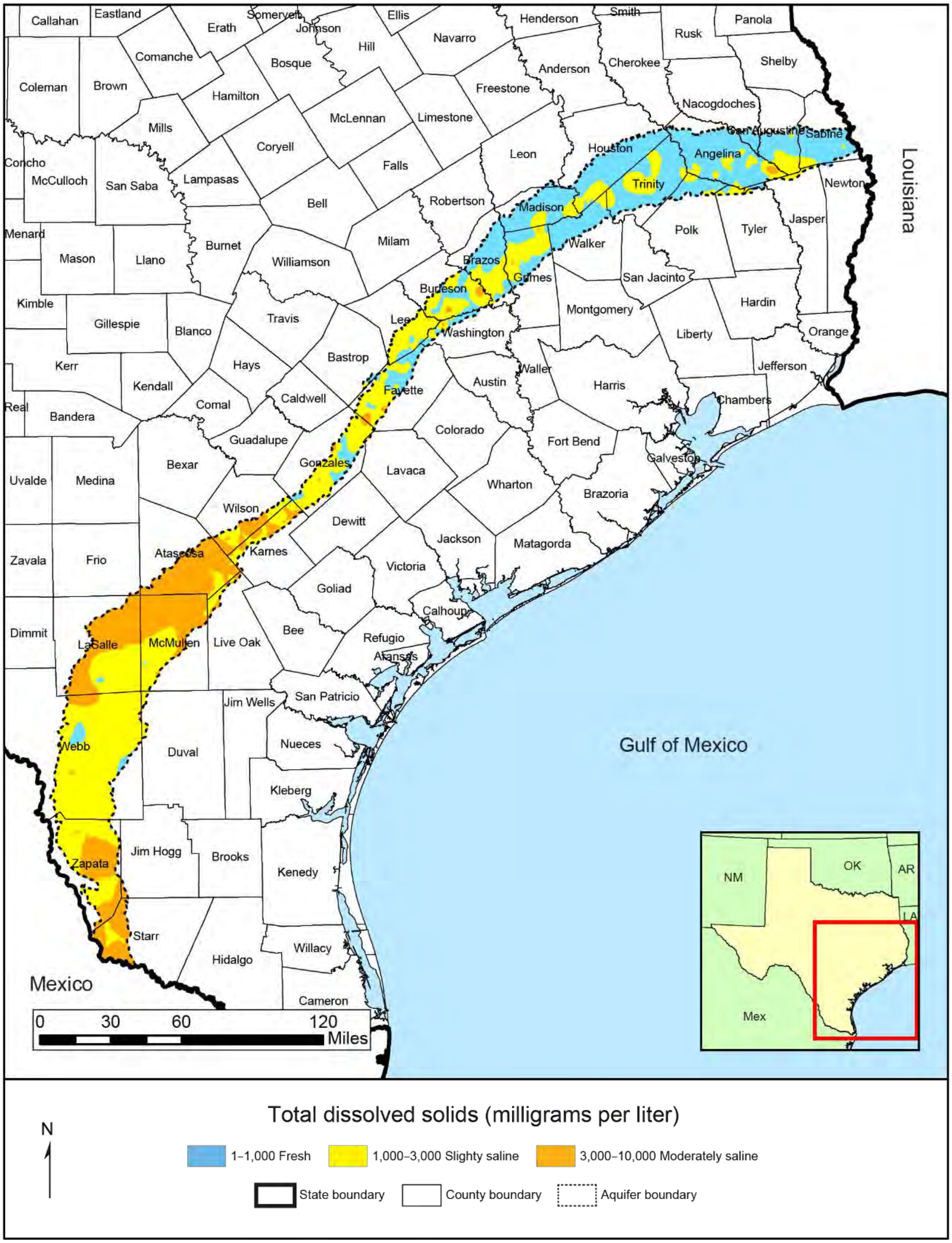


Figure 6-107. Total dissolved solids in the Yegua-Jackson Aquifer.

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Texas Permian Future Generations

Public Comments on Land Application of Produced Water;
RPN 2026-006-309-OW

EXHIBIT 5

Toxic-Risk, LLC

**Toxicology & Human Health Risk Assessment
Consultation and Training Services**

Date: 15 June 2026

From: George Woodall, PhD, Toxic-Risk, LLC

To: Caroline Crow, Senior Attorney, Earth Justice

Subject: Consideration of Human and Environmental Health Risk for the Proposed Rulemaking on Land Application of Produced Water (TCEQ Rule Project Number 2026-006-309-OW)

Overview

The subject rulemaking proposes to amend portions of the Texas Administrative Code to allow for an increase in the land application of treated produced water from oil and gas extraction operations that has been treated for beneficial use (TCEQ 2026a). The rulemaking is part of the implementation of SB 1145 that amended the Texas Water Code, notably transferring the permitting authority for land application of produced water from the Railroad Commission to TCEQ and granting authority to TCEQ to "establish new policies as a result of this rulemaking, because the program is new to TCEQ" (TCEQ 2026).

A series of reports were published by the Texas Produced Water Consortium (TPWC) to inform the rulemaking process (TPWC 2022, 2024, 2026). The TPWC was created by the Texas Legislature in 2021 "to bring together information resources to study the economics of and technology related to, and the environmental and public health considerations for, beneficial uses of fluid oil and gas waste" (2022).

The first report in the series (TPWC 2022) provided the framework for a pilot program to test the feasibility of using "existing technologies to effectively treat water of various quality levels." Since such facilities did not exist, pilot facilities were proposed to analyze treatment capabilities and to characterize the treated water.

The second report (TPWC 2024) provided an overview of the available technologies with a report on the establishment of the pilot projects; review of the standards (health protective exposure limits) in Texas, other states (MT, NM, CO), as well as guidelines from National and International organizations (FAO, GWPC, NRC); analyses of economic considerations; a review of the desalination technologies most appropriate for the pilot projects; and other aspects of the pilot program.

The final report in the series (TPWC 2026) documented results from 60 water samples taken from a group of five pilot projects. Chemical analyses and whole effluent toxicity (WET) tests were conducted on the samples which were acquired at various phases of the treatment processes (17 raw produced water (PW), 13 clean brine (CB) or pretreated produced water (TPW), 12 desalinated produced water (DPW), and 18 polished DPW (PDPW).

In addition to the TPWC reports, documents related to two recent Texas land application permit (TLAP) amendments were reviewed: Texas Pacific TLAP (Notice of Receipt of Application and Intent to Obtain Water Quality Permit Amendment, Permit No. Wq0005522000); and Brymer TLAP (Notice of Receipt of Application and Intent to Obtain Water Quality Permit Amendment, Permit No. WQ0005515000). These TLAP amendment applications were valuable in providing a limited basis for comparing the analyses from the TPWC reports to anticipated throughput of produced water in two locations.

Methodological Considerations and Missing Details

Missing Details on Sample Site, Treatment Processes, and Raw Produced Water Characterization. The information provided about the water sample analyses focus on comparing between the four water types (PW, TPW, DPW and PDPW); however, no information is provided about the individual sites where samples were acquired. All summary data seems to be aggregated across sites and treatment processes, making it all but impossible to be able to discriminate between the pilot project sites, and to follow the trail as water went from PW to PDPW at each site, presumably using various treatment technologies.

It seems that all of the desalination options are being treated as equivalent in this analysis. It could reasonably be assumed that each treatment process would have different efficiencies and be most effective for only some classes of compounds, with some working better with some raw PW that others. It would be useful to have information on the raw water and sampling site characteristics also known to the reader.

Simply providing a key for readers to discern these key details would be helpful. For example, do the sample IDs provide a clue as to the site? The details listed below would have been informative.

1. Some site identifier for the pilot plant where each sample was taken. The exact identity could be anonymized by using a code, if necessary.
2. Site characterization to identify which treatment processes were being used at each site when samples were taken.
3. Characterization of the raw produced water (PW) for each site would also be information, including which sites were completed by use of hydraulic fracturing.

This additional information would help the reader better understand the relative representativeness of sampling in the pilot program and be better informed about the relative effectiveness of each treatment process. Appendix 1 (contained in an associated spreadsheet) provides a wealth of detailed information but does not include any discernable way to parse out any of the missing details listed above.

For example, Table 5 in the final TPWC report (TPWC 2026) aggregates results across each treated water type (PW, TPW, DPW and PDPW) for a number of chemical species (e.g., benzene) and physical chemical properties (e.g., specific conductance). These details are informative but do not allow a discrimination of how well the various processes steps perform on the diverse set of PW being treated. These details would be helpful in understanding the effectiveness of each process and how well each performs across the various raw PW being treated.

Whole Effluent Toxicity (WET) Testing.

It is commendable that WET testing was performed in these analyses. It may be advisable for WET testing be performed on the PDPW from each site before it can be released to surface waters as a permitting requirement, and for WET testing to be performed on some regular on-going basis. Testing for specific chemicals can be informative; however, toxicity testing of the PDPW (especially if it is being released to receiving waters) may be most cost-effective method for protecting aquatic species, and to provide some assurance that the waters are safe for downstream communities to use for drinking water. Additional testing for individual toxic components to identify which chemical or other parameter is causing the toxicity could then inform what adjustments may be needed to correct the problem.

More specifically related to the TPWC (2026) report, a definition of the “control water” seems to be missing. Was the control water distilled water, water from a municipal system, or something else?

Another missing detail from the WET test methods was whether a blank control (i.e., 100% control water) was included for each of these toxicity tests. If so, what were the results? A blank control is standard practice in most toxicity testing protocols. Mention is made that the 98-hour acute tests are less reliable because organisms are stressed from lack of feeding in this protocol, which is a reasonable observation; however, a negative control (100% control water) would be most useful regardless any other limitations to the test protocol.

The results provided in Table 6 compare the DPW and PDPW samples across the various WET tests conducted. As noted earlier, including information only on the average and maximum no observed effect level (NOEC) can mask important information. The table below (Table 1) shows a pivot table analysis of the Appendix H spreadsheet to include the count of samples (Count of NOEC) along with the minimum and maximum NOEC for each of the tests of the polished DPW (i.e., the final “product”). Additional analyses to test the effectiveness of the treatment methods was not possible because those data were not provided in the report or the appendices.

Table 1. Pivot table analysis of Appendix H - WET Test Results from the TPWC (2026) Report

Row Labels	Count of NOEC (%)	Min of NOEC (%)	Average of NOEC (%)	Max of NOEC (%)
Polished DPW	**95**	**12.5**	**93.62**	**100**
Growth	**17**	**12.5**	**79.69**	**100**
Fathead minnow-Chronic	14	12.5	85.58	100
Green Algae-Chronic	3	12.5	54.17	100
Reproduction	**14**	**100**	**100.00**	**100**
Ceriodaphnia-Chronic	14	100	100.00	100
Survival	**64**	**25**	**95.70**	**100**
Ceriodaphnia-Acute	18	25	87.50	100
Ceriodaphnia-Chronic	14	100	100.00	100
Daphnia-Acute	2	100	100.00	100
Fathead minnow-Acute	16	100	100.00	100
Fathead minnow-Chronic	14	50	96.43	100
Grand Total	**111**	**12.5**	**87.84**	**100**

Constituent Analytical Concerns

Analytes Missing from the Comparison to Regulatory Water Quality Standards. Some key water pollutants and characteristics were not analyzed, with no reasoning provided in any of the TPWC reports (TPWC 2022, 2024, 2026). Some were disinfection by-products, which are mentioned here because it is noted in Figure 1 of the TPWC (2026) report that chlorine dioxide was listed as a potential oxidant to be used in pre-treatment. If the raw PW being treated is high in organic compounds, chlorinated by-products could be generated in levels which might be a concern, depending on the final use of the PDPW. Would there be a need to include later analyses of the water where this process is being used to ensure those compounds are removed in later processing steps? The list below includes the missing analytes, with an asterisk (*) added to denote the disinfection agents and by-products.

- 1,1-Dichloroethylene
- 2,4,5-TP
- Asbestos (fiber > 10 micrometers)
- Beta particles and photon emitters
- Carbofuran
- Chloramines (as Cl2) *
- Chlorine dioxide (as ClO2) *

- Chlorite
- Color
- Corrosivity
- Di(2-ethylhexyl) adipate
- Di(2-ethylhexyl) phthalate
- Dichloromethane
- Diquat
- Endothall
- Epichlorohydrin
- Foaming Agents
- Haloacetic acids (HAA5) *
- Lindane
- o-Dichlorobenzene *
- Odor
- Oxamyl (Vydate)
- p-Dichlorobenzene *
- Picloram
- Total Trihalomethanes (TTHMs) *

Again, the identification of which processes led to the results reported would be helpful to discern which processes were more robust and for which pollutants. This information might prove helpful for deciding which process (or processes) are most appropriate to use at a particular site requesting a new or amended TLAP.

<u>Limited Statistical Analyses</u>. The TPWC (2026) report also states that “of the 23 parameters with detected values, 22 had average values that satisfied the TCEQ drinking water limits.” Instead of aiming for the average value, should not the goal be for the maximum detected value to be below the TCEQ DWL (i.e., all measured values would be below the limit)?

Exposure Concerns for Human and Environmental Health

<u>The Nature of Produced Water vs. Domestic Wastewater</u>. Because the permitting program for PW land application is being modeled on the existing program for domestic wastewater, it should be noted that there are distinct differences between each. Many of the compounds noted in the TPWC reports (2022, 2024, 2026) are not found in domestic wastewater and *vice versa*.

<u>Future Work</u>. The conclusion section of the TPWC (2026) report notes that “ongoing and future work is investigating correlations among water chemistry and toxicity results” among other

activities. Although this seems a logical pursuit, it may be prudent in the interim to perform key toxicity tests on a regular basis on each PDPW until these investigations are complete. Depending solely on analysis of chemical and water quality parameters may miss key toxic components. As noted in the preceding discussion on WET testing, follow up analyses could be used to determine which pollutant(s) are responsible for the effects noted in a WET test, and help inform which analytes will be most appropriate to be health protective. Once the responsible chemical(s) and/or water quality parameters for the toxicity is established, appropriate adjustments can be made to the processes leading up to production of the PDPW.

Concerns Regarding Volume of PDPW to be Applied to Land and/or Released. In both the TX Pacific TLAP (TCEQ 2026c) and Brymer TLAP (TCEQ 2026d) were specifications on the anticipated average flow rate to be applied to a specific number of acres.

The TX Pacific TLAP states that “a daily average flow of 2,730,000 gallons per day via irrigation of approximately 102 acres of non-public access rangeland.” This is effectively equivalent to one inch of rain per day on all 102 acres. The average annual rainfall in Reeves County, TX is 11". In contrast to the TX Pacific TLAP, the application rate for the Brymer TLAP is equivalent to 0.3" of rain per acre per day. The annual average rainfall in Atascosa County (the county where this facility is located) is approximately 32".

As there will still be residual salinity in the final PDPW along with a number of other constituents for each of these locations, will there be an accumulation in the soil over time, will those constituents affect the properties of the receiving soil and the underlying groundwater, and whatever crop is planted on those acres? The applications seem to be silent on these concerns.

Item 9 in the application asks if any testing has occurred. In the TX Pacific TLAP the response includes a notation that “no discharge has occurred yet.” It is not clear from this response whether this indicates that toxicity testing will occur once discharges begin.

Another concern is the potential for these processes to increase emissions to air. In regulatory guidance provided by TCEQ (2025), the only emissions discussed are VOC from storage tanks using standard calculations. Some of the processes noted in the Consortium Reports (TPWC 2024, 2026) allude to the potential for air stripping of VOC (degassing) of the DPW as part of the final process leading to production of PDPW. There seems to be no estimates on the level of VOC emissions anticipated from these processes in any of the TPWC (2022, 2024, 2026) reports.

As an example, the average of detected concentration of benzene in the raw PW from Table 5 in the TPWC (2026) report is 6.32 mg/L, with the level of benzene in the final PDWP below detection limits. Assuming the treatment processes are likely to be emitting benzene to air (no other information is provided in any of the TPWC reports) and applying that concentration to the anticipated flow rate from the TX Pacific TLAP, the calculated emission rate to air would result in this facility becoming a major source of hazardous air pollutants (HAP) under the Clean Air Act based on that one pollutant, as shown below.

$$6.32\ mg/L\ \times 3.785\,L/gal = 23.92\ mg/gal$$

$$23.92\,mg/gal \times 2{,}730{,}000\ \ gal/day = 65{,}304{,}876\,mg/day$$

$$\frac{65{,}304{,}876\ mg/day}{453{,}592.37\,mg/lb} = 144\,lb/day$$

$$\frac{144\,lb/day \times 365\,day/yr}{2{,}000\,lb/ton} = \frac{52{,}550\,lb/year}{2{,}000\,lb/ton} = 26.27\,tons/year$$

This set of calculations is based on the only information provided in the available reports. Further information to provide some the missing details noted in prior comments could refine these results; regardless, this demonstrates a concern for the transference of pollutants from one medium (water) to another (air).

Recommendations

Based on the points raised in this report, the following recommendations are provided to help bolster this rulemaking process, to better ensure protection of human health and environmental health, and provide better information to the public and regulated community on the best methods for the treatment of produced water for beneficial uses.

- Provide identifiers for the pilot project sites and include those details in the analytical details (i.e., the appendices to the TPWC [2026] report).
- Better characterize the raw PW, and the processes used at every treatment step for each site.
- Report results based on these more detailed subcategories instead of aggregating data by water type across sites.
- Provide rationale for why several important analytes were not included in the pilots, and how they will be addressed in future rulemaking.
- Provide greater detail on the missing details on the WET tests reported in TPWC (2026), most notably the definition of “control water” and results from blank controls if those were included but not reported.
    - For future WET tests, providing these details would improve the completeness of reporting those results.

- It is advised that WET testing be performed on the PDPW from each site before it can be released to surface waters as a permitting requirement, and for WET testing to be performed on some regular on-going basis thereafter.
- Provide more detailed analysis on the potential for air pollution issues from these processes to reduce or eliminate transference of pollutants between media.

References

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TCEQ 2026a. *Land Application of Produced Water*. Rule Proposal Website (https://www.tceq.texas.gov/rules/prop.html), last accessed on June 15, 2026.

TCEQ 2026b. *Commission Approval for Proposed Rulemaking, Chapter 309 Domestic Wastewater Effluent Limitation and Plant Siting, Chapter 210 Use of Reclaimed Water, Land Application of Produced Water, Rule Project No.: 2026-006-309-OW*. Interoffice Memorandum from Cari-Michel La Caille, Director of Office of Water.

TCEQ 2026c. *Notice of Receipt of Application and Intent to Obtain Water Quality Permit Amendment, Permit No. WQ0005522000*. Issuance Date: May 11, 2026.

TCEQ 2026d. *Notice of Receipt of Application and Intent to Obtain Water Quality Permit Amendment, Permit No. WQ0005515000*. Issuance Date: March 19, 2026.

TPWC 2022. *Beneficial Use of Produced Water in Texas: Challenges, Opportunities and the Path Forward*. Texas Tech University, Lubbock, TX

TPWC (2024). *Beneficial Use of Produced Water in Texas*. Texas Tech University, Lubbock, TX

TPWC (2026). *Produced Water Treatment Pilot Testing: Water Quality Report*. Texas Tech University, Lubbock, TX

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09/2002-09/2025 **Toxicologist**, Hazardous Pollutant Assessment Branch (HPAB), RTP, NC:

Dr. Woodall was a Primary Leader of a project in the Health and Environmental Risk Assessment Research Program to analyze and investigate a multi-dimensional approach to performing dose-response assessment. Investigations in this project was focused on the inter-relationship of adverse health outcomes (responses) to three key elements of exposure: concentration (how much), duration (how long), and critical timing of exposures (when).

Dr. Woodall also led the Risk Assessment Training and Experience (RATE) Program from 2019 until his retirement. As the name implies, RATE provides training ranging from basic concepts for a novice risk assessor (or the public) to more advanced topics useful in developing a complex risk assessment. A key element of the RATE training modules is an acknowledgement that risk assessment is a "team sport", requiring wide-ranging expertise which is not often found in any one individual. From 2020 to 2025, he led a Risk Assessment Training series for the Office of Pollution Prevention and Toxics (OPPT) incorporating RATE training modules along with related topics, and as the series progressed, it garnered participation across multiple other EPA offices.

He initiated a project to develop an agency-wide strategy for managing and communicating environmental health science (EHS) information using sematic matching and ontologies. This project began in 2017 while Dr. Woodall served as the Acting Coordinator for the Science and Technology Policy Council within the Office of the Science Advisor on a 120-day detail. This project developed a data coordination blueprint that is flexible and sustainable, based in large part on the definition of needs established in a workshop held at North Carolina State University in September of 2014 on *Development of a Framework for an Environmental Health Science Language* (EHS Language Workshop) and reported in EHP (http://dx.doi.org/10.1289/ehp.1510438). The focus of this project is to move from simple definitional constructs (glossaries) to much more harmonized, integrated, and interoperable taxonomies and ontologies for specific knowledge domains. The work in this project has proven useful in the application of systematic review across the Agency, paving the way for better coordination of the data streams coming from the "omics" technologies and the more traditional "legacy" data commonly used in agency risk assessments.

Dr. Woodall has and continues to serve in various roles in support of Agency assessments, most notably the IRIS and PALs programs. Past roles in the IRIS Program have included involvement in a pilot project (2003-2005) for the improvement of RfC and RfD development that includes the generation of guideline values for acute and other less-than-lifetime exposure durations for inclusion into IRIS. He is a member of the Inhalation Work Group, and the Systematic Review Work Group supporting work in the IRIS Program. He was also a member of a "Sprint Team" in late 2016 which was charged by the Acting NCEA Director to provide recommendations for streamlining and improving the process of assessment development, and for strengthening the overall program.

He was the project leader in planning and development of an EPA Workshop (State-of-the-Science Workshop on chemically induced Mouse Lung Tumors: Applications to Human Health Assessments) held in January of 2014, and served as the Workshop Moderator. In planning the workshop, he led a diverse and often contentious group of experts from across the Agency, other federal agencies, academia, environmental advocacy groups, and industry. The resulting 2-day workshop elicited discussion on several lines of research investigating whether or not lung tumors in mice are relevant to humans. The meeting was convened with no expectation of consensus; however, the discussions are informing the IRIS Assessments for the compounds ethylbenzene, naphthalene and styrene.

During the Autumn of 2015, he served as a Technical Advisor to the World Health Organization (WHO) as they began the process of revising their Global Air Quality Guidelines. He participated in the WHO Expert Meeting on the topic in Bonn, Germany from September 29 – October 1, 2015.

From 2013 until 2018, Dr. Woodall led a multi-agency Air Sensors Health Group (ASHG), with representation from across EPA (OAQPS, ORD, and Regions); ATSDR; NIEHS; NIOSH; NIH/NLM; USACE; US Army; and Argonne National Laboratory. The charge for this group was to provide context and useful interpretive tools for informing the public on the relative health effect potential from short-term exposures to air pollutants, using the results from inexpensive, hand-held sensors. A review of this work was published in 2017 and is available online (http://dx.doi.org/10.3390/atmos8100182).

He led an informal staff-level interagency working group from 2011-2016 in a multi-year effort to change the way agencies across the federal government share data resources (e.g., databases of toxicological data) with the strategic goal to develop a common pool of information used in risk assessments. The basic premise of this effort is observation that the information used in risk assessments remains the same and is interchangeable, regardless of the Agency or the purpose of the resulting risk assessment. Efforts both preceding the formation of the working group and since have resulted in topic-related seminars and workshops (2004 EPA Science Forum Session; 2007 Toxicology and Risk Assessment Workshop; and a 2011 Workshop on Exposure-Response Arrays). He chaired a roundtable session at the annual meeting of the Society of Toxicology (SOT) in 2015 on the topic "Confronting and Overcoming the Barriers to Sharing Toxicological Research Data for Risk Assessment in the 21st Century," and is Chair for the Informational Session "Supporting Open Data in Toxicology" at the March 2017 SOT Meeting. Another related effort is the development of recommendations for the development of "exposure-response arrays" – graphical depictions of the available dose-response information for a chemical – to assist in both the hazard identification and dose-response assessment portions of an overall assessment of health risk. Most recently while serving on detail to the Office of Science Advisor (OSA) as the Acting Coordinator for the Science & Technology Policy Council (STPC) and described in more detail below, he initiated a project to develop "An Agency-wide Strategy for Managing and Communicating Environmental Health Science (EHS) Information" which will help advance these same principles.

From 2004-2015 he served as the EPA/ORD representative on the National Advisory Committee for Acute Exposure Guideline Levels (NAC/AEGL). Duties included acting as a Chemical Manager and Chemical Reviewer. Most recently, he worked collaboratively with NHEERL scientists to incorporate updated neurological study data into revised PBPK models to revise the Toluene AEGL values. Proposed revisions to the AEGL Technical Support Document were presented to the NAS Subcommittee on AEGLs at their April 2013 meeting. The final values were published in 2014 by the National Academies Press (http://www.epa.gov/oppt/aegl/pubs/toluene_final_%20v17_jun_2014.pdf).

He served as a member on several cross-agency work groups, including support for the Risk and Technology Review (RTR) Program within the Office of Air Quality Planning and Standards (OAQPS). He has also provided support to OAQPS on work groups to add n-propyl bromide and hydrogen sulfide to the list of hazardous air pollutants. His support work with RTR has resulted in multiple Agency Awards from both the Office of Research and Development (ORD) and from the OAQPS.

From 2006-2009, Dr. Woodall served on an international Expert Group for revisions to the OECD acute inhalation test guidelines, which lead to incorporation of consideration of concentration by time (C x t) in the traditional acute inhalation test guideline (TG 403), and addition of an alternative guideline for classification and labeling (TG 436). Within that group, he led a Performance Assessment Group which consisted of inhalation toxicology and statistical experts from around the world in analyzing the validity and reliability of the results obtained from these test guidelines using historical data and statistical simulations. He has continued his engagement on OECD Projects related to his expertise in inhalation toxicology.

Dr. Woodall was a member of the Chemical Decontamination Standards Working Group (2005-2008), which was chartered under the Subcommittee for Decontamination Standards and Technologies (SDST) under the White House Office of Science and Technology Policy (OSTP). The working group was established to develop contingent guidelines for application in an intentional release of toxic chemical agents (e.g., a terrorist event). He was called upon by the SDST co-chairs to lead an effort to develop a final document.

From 2003 – 2006 he led the development of an Agency-wide acute inhalation risk assessment methodology. Recent efforts on this project have focused on making the methodology available for application in Homeland Security and internationally through the Office of Economic Cooperation and Development (OECD). Dr. Woodall led the OECD Expert Group on developing an Acute RfC (ARfC) Guidance Document; the final Guidance Document was published August 2011 (http://www.oecd.org/chemicalsafety/testing/48542016.pdf).

04/2017-08/2017 Acting Coordinator for the Science & Technology Policy Council (STPC) [120-day Detail], Office of the Science Advisor (OSA), EPA, Washington, DC:

The objective for this detail was "to provide OSA exceptional scientific and technical support and to provide the candidate an opportunity to learn about OSA/ORD, while developing or increasing their leadership skills." In this role, Dr. Woodall fulfilled the following duties:

1. Lead STPC staff members and responsible for overall coordination of their activities as they support various activities (leading workgroups, preparing materials, developing guidance/training etc.) for OSA and the STPC.
2. Lead development of the meeting agenda and materials for the March STPC and STPC Scientific Support Panel meetings (includes briefing OSA management and the Science Advisor).
3. Facilitate workgroup activities, applying knowledge of scientific/engineering principles and practices to address scientific and technology issues that impact the Agency.

4. Coordinate the review and analyses of complex and sensitive scientific or technical products and makes recommendations for resolution of significant issues.

He was also successful in proposing an OSA-funded project for FY 2018 to develop “An Agency-wide Strategy for Managing and Communicating Environmental Health Science (EHS) Information.” He is working collaboratively with the STPC Coordinator to fulfill this project with active collaboration from across the Agency, and contractor support through the Office of Environmental Information.

07/2009-10/2009 **Acting Assistant Laboratory Director [120-day Detail]**, National Health and Environmental Effects Research Laboratory (NHEERL), RTP, NC:

In this detail Dr. Woodall was responsible for overseeing the performance of the Air Program within NHEERL, maintaining and certifying completion of annual performance measures (APMs), coordination of research program across other programs within NHEERL as well as across the air programs of other ORD Labs and Centers. In this role, Dr. Woodall led the organization of a one-day workshop focusing on the NHEERL Air Program and creating a vision for the future in a climate of budget limitations and for working in a more collaborative fashion across ORD and the Agency.

02/2008-06/2008 **Supervisory Toxicologist [120-day Detail]**, Hazardous Pollutant Assessment Group (HPAG), RTP, NC:

Dr. Woodall served in a 120-day detail as the Acting Branch Chief for HPAG. In this role, Dr. Woodall was responsible for the day-to-day function of HPAG and supervision of all members of the Group. Duties also included the allocation of funds and personnel to meet HPAG obligations, as designated by the NCEA-RTP Division Director. Matrix management was applied to carry out the necessary steps, working cooperatively with the rest of NCEA-RTP.

04/2000-09/2002 **Senior Toxicologist**, American Petroleum Institute, Washington, DC:

Responsibilities included managing and directing research projects on behalf of two technical committees comprised of toxicologists and experts from other health-related fields from the member companies of the API; developing consensus within the technical committees on the course of action that needs to be taken to meet research goals; and leading the preparation of the papers and reports resulting from the research. Dr. Woodall also helped manage the formation of a research consortium for the purpose of conducting a 5-year $20-million+ epidemiological research project conducted in China. He organized meetings and research symposia on cutting-edge issues, including a 3-day symposium on hydrogen sulfide which was co-sponsored with US EPA. He provided comment on pending regulation with an impact on the petroleum industry using arguments based on sound science. Other responsibilities were to provide knowledgeable consultation on toxicological issues to other API Staff or to member companies as needed.

03/1995-03/2000 **Senior Toxicologist**, Pacific Environmental Services, Inc., RTP, NC:

Responsibilities included management of projects, and providing technical assistance and consultation for other projects, as needed. Projects for the U.S. EPA included: MACT Rule Development for the Surface Coating of Miscellaneous Metal Parts and Products; Dispersion and Exposure Modeling Analyses; Update and Maintenance to the EPA’s Factor Information and Retrieval (FIRE) Database

System (including deriving PM 2.5 factors from PM10 and TSP factors); and Studies to Support Ozone NAAQS Implementation.

10/1992-03/1995 **Toxicologist**, Science Applications International Corporation, Durham, NC:

Projects while at SAIC included: development of a targeting algorithm for exposure to silica to determine the potential for silica to affect human health; a Review of Health Assessment Data on the Fresh Kills Landfill on Staten Island in New York City; a Risk Screening Analyses of Cement Kilns in Kansas, an Inventory of Reactive Volatile Organic Compounds (RVOC) from Consumer Products; the development of an Environmental Justice Data Base to allow analyses using GIS-based software; and a Comparison of the Methods Used to Protect Public Health in the United States and Russia.

06/1987-10/1992 **Toxicologist**, TRC Environmental Corporation, Chapel Hill, NC:

Projects while at TRC included: Toxicity and Environmental Fate of Mercury; Toxicity Summary of Chlorine and Hypochlorite, and Review of Chlorine in Drinking Water; an Air Pollution Study in the Kentucky - Ohio - West Virginia Tri-state Area (including SO_2, NO_x, CO, particulates, and H_2S); a follow-up Epidemiological Study in the Kentucky - Ohio - West Virginia Tri-state Area; Evaluation of Carbon Tetrachloride Emissions at a pesticide manufacturing facility (risk assessment); and Development of Locating and Estimating (L&E) documents for the toxic air pollutants methyl chloroform, methyl ethyl ketone, toluene, xylenes, and chlorobenzenes.

08/1986-06/1987 **Toxicology Trainee**, Department of Toxicology, North Carolina State University, Raleigh, NC.

Mr. Woodall performed analyses with various microorganisms capable of degrading chlorinated hydrocarbons through both catabolic and co-metabolic degradation.

10/1985-07/1986 **Interim Laboratory Director/Instructor**, Environmental Health Services Laboratory, Department of Environmental Health, East Tennessee State University, Johnson City, TN.

Mr. Woodall oversaw the daily operations in the contract services of the laboratory on a interim, full-time basis. Duties included the teaching of a graduate-level course in environmental microbiology.

08/1984-10/1985 **Laboratory Technician**, Environmental Health Services Laboratory, Department of Environmental Health, East Tennessee State University, Johnson City, TN.

Education

-	North Carolina State University	Ph.D.	Toxicology	1996
	Thesis Title:	*Effects of Dietary Casein Levels on the Activation and Metabolism of Promutagens by Rat Hepatic S9, Microsomes and Cytosol*.		
-	East Tennessee State University	M.S.E.H.	Environmental Health	1985
	Thesis Title:	*Mutagenic Activity Associated with Cooling Tower Waters*		
-	University of Florida	B.S.	Microbiology and Cell Science	1983

Professional Affiliations

Society of Toxicology – 35-plus year Member;

2019-2025 Lead for the **Risk Assessment Syllabus** webinar series
2020-2023 Leadership Chain for the **Science Liaison Coalition**
(https://www.toxicology.org/slc.asp)
2016-2020 SOT representative to the **Scientific Liaison Coalition**
2018-2019 President for the **Risk Assessment Specialty Section** (RASS)
2013-2015 Secretary-Treasurer for the **Risk Assessment Specialty Section**
2016-2018 Member of the **Specialty Section Communication & Collaboration Group**

North Carolina Society of Toxicology

Society for Risk Analysis

Genetics and Environmental Mutagenesis Society (GEMS) – Lifetime member;

President from November 2020 – November 2021
Councilor 2012-2014 and again in 2014-2016

Sigma Xi, Associate Member

Awards and Other Recognition

ORD Diplomacy Award 2023 – "For providing the highest quality customer service and building collegial collaboration and partnerships with Individual Awards and groups outside ORD." Awarded in March 2025.

EPA Bronze Medal Awards for Commendable Service

- **2021** – OCSPP Leaders in Science Award for the "OPPT Risk Assessment Training Production Team" which was led by Dr. Woodall.
- **2017** – Awarded by ORD (Robert Kavlock) for "Exceptional technical work evaluating the health effects literature on n-propyl bromide for addition to the list of hazardous air pollutants in support of OAR and OCSPP."
- **2016** – Awarded by OAQPS (Janet G. McCabe) for "Outstanding performance, dedication, and achievements of the Brick Manufacturing NESHAP Project Team."
- **2016** – Awarded by OAQPS (Janet G. McCabe) for "Extraordinary efforts in producing a high quality rule that will achieve substantial reductions in air toxics without posing excessive economic burden on the industry."
- **2015** – Awarded by OCSPP (James J. Jones) for support of the Acute Exposure Guideline Level (AEGL) Program; "For completion of a strong scientific leadership and collaboration effort that

culminated with development and acceptance of AEGLs as world standards for emergency response activities."

- **2007** – Awarded by ORD (George Gray) for Program support of the Risk and Technology Review Team; "Exceptional support in development of the risk and technology review Group I sources rulemaking.".
- **2003** – Awarded by ORD (Paul Gilman) for "Promoting strong science in Agency Decisions" related to Program Support to OAQPS in the Residual Risk Program.

Science and Technology Achievement Award (Level III)

- **2008** for the paper: *A review of the mutagenicity and rodent carcinogenicity of ambient air* (Claxton and Woodall, 2007; http://dx.doi.org/10.1016/j.mrrev.2007.01.001).
- **2007** for the paper: *Acute health reference values: Overview, perspective, and current forecast of needs* (Woodall, 2005; http://dx.doi.org/10.1080/15287390590912199).

Exceptional/Outstanding ORD Technical Assistance to the Regions or Program Offices (Individual awards)

- **2021 –** Exceptional Technical Assistance to the Regions or Program Offices Award for contributions to the CPHEA 2021 Office of Air Research Support Team.
- **2010 -** For outstanding technical assistance to Agency program offices as a member of the ORD Residual Risk and Technology Review Team.
- **2009 -** For outstanding technical assistance to Agency program offices by the development of the document *Graphical Arrays of Chemical Specific Health Effect Reference Values for Inhalation Exposures*

Superior Accomplishment Recognition Awards (Individual Awards)

- **2015 -** "In recognition for outstanding and highly significant contributions in providing essential support to the Program Offices through his participation on the Risk and Technology Review (RTR) Assessment Plan review panel and by providing input to regulatory preambles and response to comments documents relating to the RTR. In addition, George has worked with the Program Offices to develop criteria helpful in determining the appropriate reference value to use in different situations. George is working to incorporate his knowledge on reference values into a reference value array tool which will be available to the broader agency."
- **2014 -** "In providing exemplary service and leadership in the organization of the Mouse Lung Tumor Workshop in support of the IRIS Toxicological Reviews of Ethylbenzene, Styrene, and Naphthalene. George showed an amazing level of leadership in the development, planning, and execution of the workshop. George led teams of internal and external scientists to develop and plan the workshop. George worked with the contractor to ensure the logistics were in place, and negotiated with EPA staff to arrange for complex telecommunications logistics. George led and chaired the workshop, which has been hailed by experts from all stakeholder groups as one of the IRIS Program's most successful and useful workshops. George set the bar for the rest of the

program on what excellent workshops should be. Through George's hard work and leadership, the IRIS Program won well-deserved recognition for its workshops, and the Agency has been able to engage with our stakeholders on the current science about the controversial subject of the development of mouse lung tumors following exposure to ethylbenzene, styrene, and naphthalene."

- **2011** – Contributions in the development of IRIS Assessments and development of improvements to risk assessment methodology, in particular exposure-response arrays.
- **2010 –** Use of Sound Science in Risk and Technology Reviews to address concerns regarding malfunction emissions.
- **2010 –** Leadership in the development of a draft styrene assessment, contributions to the IRIS Program, and providing support to the Program Offices.
- **2009 –** Significant contributions to development of risk assessment products by NCEA, including development of reference value arrays.
- **2008 –** Significant contributions to the products produced by the HPAG; lead roles in the development of AEGL assessments for xylene, toluene, NOx and SO2; and for service as ad-hoc advisor to the PALs program of NHSRC.
- **2007** – For support to Regional and Program Offices, in particular for support to the Superfund Technical support Center in Region 7.
- **2006** – In recognition for productive, persistent and high quality efforts in advancing the capacity of the Agency to perform assessment of health effects due to acute exposures to environmental toxicants.
- **2005** – For sustained excellent service to the Program Offices, in particular OAQPS.

On-the-spot Awards (Individual award)

- **2007 -** for providing timely support to Region 7 colleagues in response to a chemical spill incident.
- **2006 -** for Presentation to the Office of Management and Budget on the Acute RfC Method document.
- **2005 -** Coordination of the 36th meeting of the National Advisory Committee for Acute Exposure Guideline Levels (NAC/AEGL) in Research Triangle Park.
- **2005 -** Contributions to the Residual Risk Work Group on Ethylene Oxide.
- **2005 -** Coordination of the Agency Review of four Pilot Acute Assessments and the Draft Acute RfC Methodology.
- **2004 -** Contributions to the EPA Science Forum 2004 in coordinating a cross-agency set of presentations on the subject of shared data resources.

- **2004 -** Commendation for planning and execution of the development of the Draft Acute RfC Methodology.
- **2003 -** For dedicated performance above normal duties in gathering critical elements for the ORD Incident Coordination Team "Response Toolkit" in preparation to respond to any future national emergency.

2006 Quality Step Increase

Letters of Commendation

- **2024** – a letter of appreciation from the Embassy of the United States of America, Lima, Peru for support in developing and delivering the Risk assessment Training Experience (RATE) workshop, "Cooperation on Heavy Metals Risk Communications, Characterization, and Management Tools and Methodologies to Support and Promote Citizen Participation". The workshop what held from February 20-22, 2024, in collaboration with Peru's Ministry of Health.
- **2021** – a letter of appreciation from the Toxicology Forum recognizing leadership and organization of the Scientific Liaison Coalition and their recent webinar, "*How to Make Your Little Data Big by Being FAIR*".
- **2008 -** from Society of Toxicology President George Corcoran for providing an invited presentation to the American Industrial Hygiene Association's Professional Conference for Industrial Hygiene in Louisville, KY (October, 2007).
- **2005 -** from Mickey Leland National Urban Air Toxics Research Center for providing an invited presentation to the First Annual Air Toxics Workshop in Houston, TX.
- **2004 –** From Paul Gilman (AA for ORD) for commendable service to the ORD Red Team, a special group asked to provide service in the event of a catastrophic event such as September 11.
- **2003 -** From Kevin Teichman (Office of Science Policy Director) for ORD Program Support to OAQPS in the Residual Risk Program.

Publications

Peer-reviewed Articles

Woodall, G.M., S.F. Kobylewski-Saucier, L. Carlson, R. Shaffer, A. Luke, B. Schulz, and E. Snyder (2025) *Comparative Review of Human Health-Based Risk Values*. *Toxicological Sciences*, 207(1), 1–19 https://doi.org/10.1093/toxsci/kfaf092

Woodall, G.M., M.M. MacDonell, and B.N. Peshlov (In preparation) *Health-Based Reference Values for Inhalation Exposure to Elemental Mercury*.

Woodall, G. M., and M.T. Taylor (2024) Graphical depictions of toxicological data, Editor(s): Philip Wexler, Encyclopedia of Toxicology (Fourth Edition), Academic Press, 2014, Volume 5, Pages 786–795, ISBN 9780123864550 (https://doi.org/10.1016/B978-0-12-824315-2.01027-7).

Thayer KA, Angrish M, Arzuaga X, Carlson LM, Davis A, Dishaw L, Druwe I, Gibbons C, Glenn B, Jones R, Phillip Kaiser J, Keshava C, Keshava N, Kraft A, Lizarraga L, Persad A, Radke EG, Rice G, Schulz B, Shaffer RM, Shannon T, Shapiro A, Thacker S, Vulimiri SV, Williams AJ, Woodall G, Yost E, Blain R, Duke K, Goldstone AE, Hartman P, Hobbie K, Ingle B, Lemeris C, Lin C, Lindahl A, McKinley K, Soleymani P, Vetter N. (2022) *Systematic evidence map (SEM) template: Report format and methods used for the US EPA Integrated Risk Information System (IRIS) program, Provisional Peer Reviewed Toxicity Value (PPRTV) program, and other "fit for purpose" literature-based human health analyses.* Environment International, Volume 169, November 2022, 107468. (https://doi.org/10.1016/j.envint.2022.107468).

Thayer KA, Shaffer RM, Angrish M, Arzuaga X, Carlson LM, Davis A, Dishaw L, Druwe I, Gibbons C, Glenn B, Jones R, Kaiser JP, Keshava C, Keshava N, Kraft A, Lizarraga L, Markey K, Persad A, Radke EG, Rice G, Schulz B, Shannon T, Shapiro A, Thacker S, Vulimiri S, Woodall G, Yost E. (2022) *Use of systematic evidence maps within the US environmental protection agency (EPA) integrated risk information system (IRIS) program: Advancements to date and looking ahead*. Environment International, Volume 169, November 2022, 107363. (https://doi.org/10.1016/j.envint.2022.107363).

Blessinger, T., Davis, A., Chiu, W.A., Stanek, J., Woodall, G.M., Gift, J., Thayer, K.A., and Bussard, D. (2020) *Application of a Unified Probabilistic Framework to the Dose-Response Assessment of Acrolein*. Environment International, Volume 143, October 2020, 105953. (https://doi.org/10.1016/j.envint.2020.105953)

Keshava C, Davis JA, Stanek J, Thayer KA, Galizia A, Keshava N, Gift J, Vulimiri SV, Woodall G, Gigot C, Garcia K, Greenhalgh A, Schulz B, Volkoff S, Camargo K, Persad AS. (2020) *Application of systematic evidence mapping to assess the impact of new research when updating health reference values: A case example using acrolein*. Environment International, Volume 143 October 2020, 105956. (https://doi.org/10.1016/j.envint.2020.105956)

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Texas Permian Future Generations

Public Comments on Land Application of Produced Water; RPN 2026-006-309-OW

EXHIBIT 6

Report with Recommendations

Date June 16, 2026

From: Nathan M. Wiser, Geologist, formerly of the U.S. Environmental Protection Agency (EPA)

To: Caroline Crow, Earthjustice Senior Attorney

Subject: Review for Certain Potential Issues Identified in Documents Associated with Proposed Changes in Texas Transferring Oversight of Produced Water Land Application from the Texas Railroad Commission (TRC) to the Texas Commission on Environmental Quality (TCEQ)

Nathan Wiser is a geologist who worked at the EPA from 1990 to 2024. For most of his career, Nathan regulated underground injection wells used for waste disposal in the Region 5 (Chicago) and Region 8 (Denver) offices, serving as a permit writer, inspector, and enforcement officer. During 2010-2016, Nathan worked within EPA's Office of Research and Development as one of investigators and authors of EPA's 2016 "*Study of Hydraulic Fracturing and Its Potential Impact on Drinking Water Resources*." In addition, Nathan also worked for EPA's Headquarters Office overseeing the Underground Injection Control (UIC) program, located within EPA's Office of Water, Office of Ground Water and Drinking Water where he developed and assisted on more than 15 online trainings about the federal UIC program. He earned his bachelor's degree in geology from the University of California, Berkeley, and his master's degree in geology from Northwestern University.

Overview

Currently most of the produced water in Texas is injected into Class II underground injection wells. This customary practice means produced water is currently brought to surface during well completion and on-going production, is returned underground into confined aquifers via injection, and does not purposefully enter the hydrologic cycle on the earth's surface. The background documentation I reviewed describe efforts undertaken by entities in Texas that support the idea that oil and gas produced water in Texas could be treated to a comparatively good water quality and then land applied as a beneficial use. If this is done, the treated produced water would enter the hydrologic cycle at the land surface.

As a conceptual matter, this has some merit, considering frequent and lasting drought conditions and the demands made on limited water supplies by population increase, agricultural and industrial needs, and increased evaporation with rising surface temperatures. At scale, however, this practice has the potential to adversely affect some aquifers, depending on the success of treatment technologies employed to remove harmful contaminants from produced water. It may also have an impact on disposal methods of the residual wastewater that remains after treatment.

2024 Texas Produced Water Consortium Report;
2026 Texas Produced Water Consortium Water Quality Report

To explore the risk of aquifer contamination, results of pilot projection described in the *2024 Texas Produced Water Consortium Report (2024 TPWC Report)* to the Texas Legislature, and the *2026 TPWC Produced Water Treatment Pilot Testing Water Quality (2026 TPWC Water Quality) Report* are summarized. The 2024 TPWC Report describes five pilot sites, all located within the Permian Basin, that operated over periods of months. The pilots used an assortment of treatment technologies to remove contaminants from nearby produced water. The throughput of the produced water ranged from about 100 to 500 barrels per day (BPD). The 2024 TPWC Report states that initial concentrations of the produced waters contained total dissolved solids (TDS) content measuring between 55,000 and 190,000 mg/L, which were lowered after treatment to TDS values below 1000 mg/L.[1]

The 2026 TPWC Water Quality Report describes that 60 water samples were collected during the pilots. Table 2 in the 2026 TPWC Water Quality Report shows 17 raw produced water samples were collected, plus 43 samples of produced waters that had undergone varying degrees of treatment.[2] The 60 water samples were analyzed for a total of 865 constituents or properties. Of these 865, treated produced water samples, analyses showed detections of 183 constituents, about 21% of the total analytes. The analyses of 18 samples from the most highly treated produced water, described as desalinated and polished, showed a total of 116 detected constituents, about 13% of the total analytes.[3]

TDS values of the desalinated and polished produced water described in the 2026 TPWC Water Quality Report ranged from 8.5 to 1370 mg/L.[4] TDS is a very common measure of general water quality, is regarded as a measure of saltiness, and is mostly composed of

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[1] Texas Produced Water Consortium Report to the Texas Legislature 2024, pp 10-11.

[2] Produced Water Treatment Pilot Testing: Water Quality Report, Table 1, pg 2. April 21, 2024.

[3] Spreadsheet "TxPWC_PilotTestingW/QReport_Appendices_FINAL" Tab App D (Any analytes detected) and Tab App F (Detected in PDPW)

[4] Spreadsheet "TxPWC_PilotTestingW/QReport_Appendices_FINAL" Tab App F (Detected in PDPW)

just a handful of naturally occurring inorganic constituents: sodium, calcium, magnesium and potassium cations plus chloride, sulfate, bicarbonate and carbonate anions. Produced water is nearly always dominated by just two, sodium and chloride. Data taken from Table 5 in the 2026 TPWC Water Quality Report shows that TDS was very high and declined considerably after treatment, as shown in Table 1 below.

Total Dissolved Solids (TDS)	**Raw Produced Water (PW)** Average Concentration (mg/L)	**Pre-Treated PW** Average Concentration (mg/L)	**Desalinated PW** Average Concentration (mg/L)	**Desalinated, Polished PW** Average Concentration (mg/L)
TDS	**131,117**	**124,333**	**317**	**352**
(No. of detections)	(17)	(3)	(11)	(15)

Table 1. Total dissolved solids from water samples at pilot study sites

However, other common produced water constituents include these four organic constituents: benzene, ethylbenzene, toluene, and xylenes (aka "BTEX"). Looking for these four BTEX constituents among the produced water samples, data taken from Table 5 in the 2026 TPWC Water Quality Report shows that BTEX was found in all the raw produced water samples but declined in concentration with increasing treatment, as shown Table 2 below.

BTEX Constituents	**Raw Produced Water (PW)** Average Concentration (mg/L)	**Pre-Treated PW** Average Concentration (mg/L)	**Desalinated PW** Average Concentration (mg/L)	**Desalinated, Polished PW** Average Concentration (mg/L)
Benzene	**6.32**	**0.2**	**0.00226**	<0.00046
(No. of detections)	(17)	(3)	(7)	(0)
Ethylebenzene	**0.229**	**0.0275**	<0.00039	<0.00039
(No. of detections)	(17)	(1)	(0)	(0)
Toluene	**5.03**	**0.541**	**0.000755**	**0.00446**
(No. of detections)	(17)	(1)	(5)	(4)
Xylenes	**2.13**	**0.195**	**0.00234**	<0.00124
(No. of detections)	(17)	(1)	(1)	(0)

Table 2. BTEX constituents from water samples collected at pilot study sites

While these results display a considerable removal of TDS and BTEX constituents, the samples collected after treatment nevertheless showed detections of more than 180 various organic and inorganic constituents. The ability to remove harmful contaminants from produced water will be critically important and should be tested robustly. The use of five modest-sized pilot projects, all located in the Permian Basin, is helpful, but further evaluation of these and potentially other treatment technologies is warranted if land application of produced water is to be conducted across all of Texas, which has several additional, copious oil and gas production plays beyond the Permian Basin.

Possible Impact to Injection Wells

Removal of contaminants from produced water will likely result in two types of water: (1) treated produced water that will be land-applied, and (2) residual wastewater with a high concentration of the removed contaminants, resulting in a high TDS waste stream that would presumably be disposed into existing or new injection wells. Wastewater with an elevated TDS concentration will likely have a higher density (specific gravity) than the raw produced water and be more corrosive. As a result, injecting this waste stream could necessitate changes to certain injection well operating parameters, including reducing maximum allowable wellhead injection pressures due to denser injectate and increased mechanical integrity testing due to higher corrosivity.

Introducing a treated produced water land application process across Texas could impact certain aspects of the existing Underground Injection Control (UIC) programs now implemented by TRC and the TCEQ and may necessitate their evaluation. Such evaluation might examine which injection well class is appropriate for disposing of this secondary waste stream, and whether any UIC program requirement may need modification, such as well mechanical integrity testing and operating controls such as injection pressure limits, when produced water treatment waste streams are injected.

2016 Texas Aquifers Study

To further consider the possibility for aquifer contamination risk, the volumes of treated produced water that might be applied to the land in the future is important, relative to the aquifer volume that would underlie the land application. In 2016, a group of geoscientists compiled the Texas Aquifers Study in response to Texas House Bill 1232, which was passed by the 84th Texas Legislature and signed into law on May 28, 2015. The Texas Aquifers Study was finalized in December 2016, addressing the law's mandate to present information on confined and unconfined aquifers in Texas, the quantity and quality of water they contain, and the volume of flows between the aquifers and the volumes of flows to surface waters of the state.

The Texas Aquifers Study states that about 60% of the water used in Texas derives from groundwater and identifies 9 major aquifers (aquifers that supply a large volume of water over a large area) and 21 minor aquifers (aquifers that supply either a large volume of water over a small area, or a small volume of water over a large area). These 30 aquifers underlie 81% of the land area of Texas.[5] Aquifers supply for about 85% of Texas agricultural water use and about 36% of Texas municipality water use.[6]

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[5] Texas Aquifers Study, Introduction, pg 1.

[6] Texas Aquifers Study, Introduction, pg 3.

The Texas Aquifers Study also shows, over the 20-year period 1995-2015 divided into 5-year increments, how groundwater levels have changed, both at the state-wide level, and for each of the 30 aquifers. In central Texas, one major aquifer, the Edwards (Balcones Fault Zone) aquifer, showed dramatic groundwater level changes during this period, gaining from high rainfall and then losing during drought, causing groundwater level changes greater than 100 feet.[7] This is attributed to the highly permeable nature of this aquifer where groundwater resides in jointed and fractured limestone (a carbonate rock). In highly permeable aquifers, precipitation events quickly increase groundwater levels while drought conditions reduce these levels. Because the Edwards (BFZ) aquifer, particularly its unconfined portion, responds rapidly to the rate of added water or the lack thereof, the aquifer is more susceptible to any contamination such as might be entrained in inadequately treated produced water applied to the land overlying the aquifer.[8]

The Texas Aquifers Study states that "*groundwater in nearly every Texas aquifer has some degree of movement into or out of surface water*." It also states that all Texas aquifers, with the possible exception of the Rita Blanca aquifer (located in the extreme northwestern corner of the panhandle), "*contribute some groundwater to surface water*."[9] These statements support the finding that the 30 aquifers identified in the Study provide significant volume to surface waters of the state. Aquifer contributions to stream baseflow (the natural groundwater-fed water in a stream not attributable to precipitation runoff) can be quite significant. The five aquifers contributing the largest share add between 38% and 72% of baseflow volumes to the streams overlying their land surface. They are the Edwards (BFZ), Pecos Valley, Edwards-Trinity (Plateau), Bone Spring-Victorio Peak, and Hickory aquifers.[10]

In addition, the Texas Aquifers Study identifies numerous examples of inter-aquifer communication, including estimated flow quantities between such aquifers. The amount of inter-aquifer flow depends on the presence or absence of impermeable boundaries between adjacent aquifers and the relative pressure difference between them. Boundaries are typically shale layers that form flow barriers located over or under more permeable aquifer material and prevent inter-aquifer communication. The Texas Aquifers Study lists inter-aquifer flow among several juxtaposed aquifers. The estimated quantified flow rates range from zero to more than 60,000 acre-feet per year.[11] This means any contamination

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[7] Texas Aquifers Study, Chapter 6: Edwards (Balcones Fault Zone) Aquifer, pp 74-81.

[8] Texas Aquifers Study, Chapter 6: Edwards (Balcones Fault Zone) Aquifer, pg 81.

[9] Texas Aquifers Study, Chapter 4: Tributary and Non-Tributary Groundwater, pg 33.

[10] Texas Aquifers Study, Chapter 3: Groundwater and Surface Water Interaction, Table 3-2, pp 29-30.

[11] Texas Aquifers Study, Chapter 5, Table 5-1, pp 43-44.

introduced to an aquifer from inadequately treated produced water might eventually flow to an adjacent aquifer.

The Texas Aquifers Study provides estimated volume of groundwater held within each of the nine major aquifers and 21 minor aquifers identified. While the total volume of groundwater actually present in each aquifer represents its uppermost volume, the practical groundwater volume is somewhat less because it is not physically possible to completely drain each aquifer. Instead, the authors estimate that the practical volume in each aquifer available, named the "estimated recoverable storage volume," is somewhere between 25% and 75% of the total volume of the aquifer. The Study displays these two storage numbers,[12] which is reproduced in Table 3 below. The largest aquifers contain estimate recoverable storage volume of more than 1 billion acre-feet while the smallest aquifers contain less than 1 million acre-feet of groundwater. Thus the largest aquifers contain about 1,000 times more groundwater than the smaller ones.

Aquifer Name	**Major or Minor**	**Estimated 25% Recoverable Storage Volume (acre-feet)**	**Estimated 75% Recoverable Storage Volume (acre-feet)**
Carrizo-Wilcox	Major	1,310,000,000	3,920,000,000
Edwards (Balcones Fault Zone)	Major	6,250,000	18,800,000
Edwards-Trinity (Plateau)	Major	11,400,000	34,100,000
Gulf Coast	Major	1,300,000,000	3,890,000,000
Hueco-Mesilla Bolsons	Major	2,250,000	6,750,000
Ogallala	Major	95,300,000	286,000,000
Pecos Valley	Major	81,000,000	243,000,000
Seymour	Major	1,280,000	3,850,000
Trinity	Major	353,000,000	1,060,000,000
Blaine	Minor	43,000,000	129,000,000
Blossom	Minor	1,770,000	5,310,000
Bone Spring-Victorio Peak	Minor	925,000	2,780,000
Brazos River Alluvium	Minor	803,000	2,410,000
Capitan Reef Complex	Minor	13,800,000	41,300,000
Dockum	Minor	373,000,000	1,120,000,000
Edwards-Trinity (High Plains)	Minor	5,930,000	17,800,000
Ellenburger-San Saba	Minor	21,800,000	65,250,000
Hickory	Minor	16,600,000	49,700,000
Igneous	Minor	16,000,000	48,100,000
Lipan	Minor	1,050,000	3,150,000

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[12] Texas Aquifers Study, Chapter 2, Table 2-1, pg 12.

Aquifer Name	Major or Minor	Estimated 25% Recoverable Storage Volume (acre-feet)	Estimated 75% Recoverable Storage Volume (acre-feet)
Marathon	Minor	375,000	1,130,000
Marble Falls	Minor	66,300	199,000
Nacatoch	Minor	1,020,000	3,070,000
Queen City	Minor	135,000,000	404,000,000
Rita Blanca	Minor	2,780,000	8,330,000
Rustler	Minor	9,230,000	27,700,000
Sparta	Minor	46,500,000	140,000,000
West Texas Bolsons	Minor	12,900,000	38,600,000
Woodbine	Minor	56,800,000	170,000,000
Yegua-Jackson	Minor	300,000,000	900,000,000
TOTAL		4,219,829,300	12,640,329,000

Table 3: Total Estimated Recoverable Storage of Groundwater in each aquifer identified in the Texas Aquifers Study

Larger volume aquifers would likely be less sensitive to contamination introduced from inadequately treated produced water than smaller volume aquifers, due to their much larger size. Nevertheless, it is also instructive to examine the volume of produced water extracted from oil and gas basins and compare that produced water volume to the size of the overlying aquifer(s), since it is likely that treatment, and hence, land application of produced water will take place near the produced water extraction area.

2022 Texas Mining Water Use Study

This final report, prepared by the Texas Water Development Board and the U.S. Geological Survey, contains a chapter devoted to oil and gas industry water use, as well as an associated appendix which provides historic volumes of produced water from eight significant and named oil and gas "plays," plus two groupings of less significant plays, spanning the years 2010 through 2019.[13] Table 4 below lists the volume of produced water from each play, using the most recent year, 2019. While the water use study has volumes from 10 different plays, Table 4 below is restricted to the four of these plays that overlap with some of the 30 aquifers identified in the Texas Aquifers Study.[14]

Play Name	Volume of Produced Water in 2019 (acre-feet)
Barnett	11,930
Eagle Ford	63,692
Haynesville	77,735

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[13] 2022 Texas Mining Water Use Study, Appx. I, Table 1-3b, pg Appendix I-26.

[14] 2022 Texas Mining Water Use Study, Appx. I, Table 1-5, pg Appendix I-35.

Play Name	Volume of Produced Water in 2019 (acre-feet)
Permian	536,364

Table 4: Volume of produced water in 2019 from certain oil and gas plays

To compare the produced water volume to the volumes in their respective overlying aquifer(s), first identify which of the Texas Aquifers Study aquifers are associated with these plays. These are listed in Table 5 below. Some of these aquifers overlie more than one play: the Carrizo-Wilcox, Queen City, Sparta, and Yegua-Jackson aquifers.

Play Name	Associated Aquifers
Barnett	Trinity
	Woodbine
Eagle Ford	Carrizo-Wilcox
	Gulf Coast
	Queen City
	Sparta
	Yegua-Jackson
Haynesville	Carrizo-Wilcox
	Queen City
	Sparta
	Yegua-Jackson
Permian	Edwards-Trinity (Plateau)
	Ogallala
	Pecos Valley
	Capitan Reef Complex
	Dockum
	Edwards-Trinity (High Plains)
	Igneous
	Rustler
	West Texas Bolsons

Table 5: Aquifers associated with oil and gas plays

To compare the volumes of each play's produced water to their overlying aquifers, the produced water volumes from Table 4 for the Eagle Ford and the Haynesville plays are combined, since it is possible the entire produced water from the two plays might be treated and land applied over just one aquifer, necessitating adding their two volumes together. Table 6 shows these reformulated volumes for the plays that include the Eagle Ford combined with the Haynesville plays.

Play Name	**Volume of Produced Water in 2019 (acre-feet)**
Barnett	11,930
Eagle Ford	63,692
Eagle Ford + Haynesville	141,427
Permian	536,364

Table 6: Volume of produced water in 2019 from certain oil and gas plays, with Eagle Ford and Haynesville plays combined for calculation purposes

The produced water volumes from each play are then divided into the volume of each aquifer, to show the percentage of the aquifer represented by each play's annual produced water volume. The results of the division calculation for each aquifer are then shown in Table 7 below. These results represent approximately the maximum percentage volume addition to an aquifer from each play's annual produced water. Since the last two columns in Table 7 display calculated ***annual*** percentages of treated produced water added to each aquifer, then as more years pass, an increasingly significant fraction of these aquifers would eventually be composed of treated produced water. Hence, the produced water must meet drinking water standards and any other applicable health or environmental standards.

As stated above, these are approximately the maximum annual percentage contributions to these aquifers from treated produced water applied to land. The actual percentages would likely be somewhat less because (1) it may not be possible that all produced water from any given play could be economically gathered, adequately treated, and then land applied to the land surface overlying just one aquifer, and (2) even if a comprehensive process to gather, treat, and land apply all produced water takes place, some fraction of the treated produced water would be the residual high-concentration brine waste stream that would have to be disposed elsewhere, presumably via injection wells. Thus, the last two columns in Table 7 below are better viewed as comparative and approximate percentage magnitudes rather than precise values.

Aquifer name	Estimated 25% Recoverable Storage Volume (acre-feet)	Estimated 75% Recoverable Storage Volume (acre-feet)	Overlapping Oil/Gas Play	Play's Annual Produced Water as Percent of Each Aquifer (at 25% Recoverable)	Play's Annual Produced Water as Percent of Each Aquifer (at 75% Recoverable)
Carrizo-Wilcox	1,310,000,000	3,920,000,000	Eagle Ford + Haynesville	0.011%	0.004%
Edwards-Trinity (Plateau)	11,400,000	34,100,000	Permian	4.705%	1.573%
Gulf Coast	1,300,000,000	3,890,000,000	Eagle Ford	0.005%	0.002%
Ogallala	95,300,000	286,000,000	Permian	0.563%	0.188%
Pecos Valley	81,000,000	243,000,000	Permian	0.662%	0.221%
Trinity	353,000,000	1,060,000,000	Barnett	0.021%	0.007%
Capitan Reef Complex	13,800,000	41,300,000	Permian	3.887%	1.299%
Dockum	373,000,000	1,120,000,000	Permian	0.144%	0.048%
Edwards-Trinity (High Plains)	5,930,000	17,800,000	Permian	9.045%	3.013%
Igneous	16,000,000	48,100,000	Permian	3.352%	1.115%
Queen City	135,000,000	404,000,000	Eagle Ford + Haynesville	0.105%	0.035%
Rustler	9,230,000	27,700,000	Permian	5.811%	1.936%
Sparta	46,500,000	140,000,000	Eagle Ford + Haynesville	0.304%	0.101%
West Texas Bolsons	12,900,000	38,600,000	Permian	4.158%	1.390%
Woodbine	56,800,000	170,000,000	Barnett	0.130%	0.043%
Yegua-Jackson	300,000,000	900,000,000	Eagle Ford + Haynesville	0.047%	0.016%

Table 7: Annual produced water volumes, expressed as a percentage of each aquifer's estimated recoverable storage volume

Recommendations

1. Additional pilot studies should be conducted and should include treatment technologies applied to produced waters from several locations beyond the Permian Basin.
2. There should be additional development of treatment technologies to remove contaminants from produced waters so that the number of detected contaminants in treated produced water is lowered before being applied to the land surface.
3. The sensitivity to contamination of each aquifer that underlies the land surface should more closely be considered. Highly permeable aquifers can transmit

contaminants quickly and there may be important land application limits established for each aquifer to ensure its protection. Further, there should be an evaluation of the volume of treated produced water added to the volume of the receiving aquifer over time, with the possibility of imposing an upper limit on the total volume of produced water added to protect each aquifer.

4. A monitoring program should be developed to analyze for contaminants in the treated produced water and the aquifers receiving the treated produced water. The monitoring program should specify which analytes to monitor, along with the frequency of analysis and the total duration of the program.
5. An analysis of the possible unintended impacts to the injection well programs in Texas should be undertaken if injection wells in Texas are a part of the produced water treatment process. This analysis should examine, at a minimum, (1) what well class would be appropriate for injecting a waste stream generated from the produced water treatment process, and (2) what injection well operational controls (e.g., wellhead injection pressure limits, well mechanical integrity testing, etc.) might be warranted considering the high density and corrosivity characteristics of such a waste stream.

Texas Permian Future Generations

Public Comments on Land Application of Produced Water;
RPN 2026-006-309-OW

EXHIBIT 7

United States
Environmental Protection
Agency

Study of the Agricultural and Wildlife Water Use Subcategory (40 CFR 435 Subpart E)

Draft April 8, 2025

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Washington, DC 20460

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Abbreviations

API	American Petroleum Institute
ATTAINS	Assessment and Total Maximum Daily Load Tracking and Implementation System
BADCT	Best Available Demonstrated Control Technology
BAF-UF	Biologically Active Filtration - Ultrafiltration
BAT	Best Available Technology
BBL	Barrel (measure of oil and produced water volume)
BPJ	Best Professional Judgment
BOD	Biochemical Oxygen Demand
BPT	Best Practicable Control Technology
Bq/kg	Becquerel per kilogram
CAS	Chemical Abstracts Service
CDPHE	Colorado Department of Public Health & Environment
COMID	Common Identifier
COWDF	Commercial Oilfield Wastewater Disposal Facility
CWA	Clean Water Act
CWT	Centralized Waste Treatment
CWTF	Commercial Wastewater Treatment Facility
DBP	Disinfection Byproducts
DMR	Discharge Monitoring Report
ELG	Effluent Limitations Guidelines
EROD	Ethoxyresorufin-O-deethylase
GWPC	Ground Water Protection Council
IARC	International Agency for Research on Cancer
IOGCC	Interstate Oil and Gas Compact Commission
Mcf	Thousand cubic feet (measure of gas production)
MSDS	Material Safety Data Sheet
NHD	National Hydrography Dataset
NOI	Notice of Intent (to discharge)

NPDES	National Pollutant Discharge Elimination System
NSPS	New Source Performance Standards
PAH	Polycyclic Aromatic Hydrocarbon
PEG	Polyethylene Glycol
PFAS	Per- and Polyfluoroalkyl Substances
POTW	Publicly Owned Treatment Works
PSES	Pretreatment Standards for Existing Sources
PSNS	Pretreatment Standards for New Sources
RN	Registry Number
SDS	Safety Data Sheet
TBEL	Technology-Based Effluent Limitation
TCEQ	Texas Commission on Environmental Quality
TDS	Total Dissolved Solids
THM	Trihalomethane
TSS	Total Suspended Solids
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
VOCs	Volatile Organic Compounds
WET	Whole Effluent Toxicity
WOGCC	Wyoming Oil and Gas Conservation Commission
WOTUS	Waters of the United States

1. Introduction and Summary

This report presents the findings of the Environmental Protection Agency (the EPA) study of discharges of produced water from oil and gas extraction activities under 40 CFR 435 Subpart E. The report was prepared by the EPA staff in the Office of Water, Regions 4, 6, and 8, and the Office of Research and Development. The EPA regulates discharges of wastewater from industrial categories to surface waters through effluent limitations guidelines (ELGs) pursuant to the Clean Water Act (CWA). See CWA sections 301, 304, and 306, 33 U.S.C. 1311, 1314 and 1316. These technology-based regulations are incorporated into National Pollutant Discharge Elimination System (NPDES) permits.

The regulations at 40 CFR 435 Subpart E allow for discharge of produced water from onshore facilities into navigable waters west of the 98th meridian if the produced water is of good enough quality for use in agriculture or wildlife propagation and the produced water is actually put to such use during periods of discharge. These onshore facilities are engaged in the production, drilling, well completion, and well treatment in the oil and gas extraction industry. The EPA promulgated the Subpart E regulations in 1979. Many changes have occurred in the oil and gas industry since that time. This study evaluates whether there are available and economically achievable treatment technologies that can reduce the discharge of pollutants from this industry. It also informs whether updates to the Subpart E regulations may be warranted.

The EPA periodically reviews the existing ELG regulations and updates them, as appropriate. The ELG Program Plan, published every two years, identifies existing industries selected for regulatory revisions and new industries identified for regulation. The ELG Plan provides a rulemaking schedule for any such activities.

This study does not announce any regulatory actions regarding 40 CFR 435 Subpart E. Readers should consult the latest ELG Program Plan and supporting documentation to obtain information regarding the EPA's planned ELG regulatory decisions (see https://www.epa.gov/eg/effluent-guidelines-plan).

The EPA's study found the following:

The EPA identified 188 existing NPDES individual permits for facilities under Subpart E. An additional 6 facilities are covered under a general permit.

Most of the existing Subpart E permitted facilities are located in Wyoming. Second to Wyoming, Colorado has the next most existing Subpart E permitted facilities. The EPA is aware of one Subpart E NPDES permit that has been issued in California, Texas, and Utah, respectively. There are also several permit applications for discharge that have been submitted to regulatory agencies in Texas and New Mexico as of March 2024.

The companies that currently hold Subpart E NPDES permits range in size from small entities that employ just a few people and produce a few thousand barrels of oil per year, to large corporations that produce millions of barrels of oil and millions of cubic feet of gas with hundreds of millions to billions of dollars in revenue and thousands of employees.

The typical pollutants that are regulated in existing Subpart E NPDES permits include oil and grease, total dissolved solids (TDS), chloride, sulfate, specific conductance and total radium 226.

Subpart E facilities that the EPA visited during this study utilize chemicals such as emulsion breakers, corrosion inhibitors, scale inhibitors, water clarifiers, and biocides to aid in oil recovery and to reduce bacteria growth and scaling in wells and in oil and produced water separation, collection, and distribution equipment. In some cases, these chemicals are added to the produced water just upstream of the discharge.

Subpart E facilities typically use oil water separation and skim pits/ponds to treat produced water. Some facilities employ aeration for sulfide reduction. The EPA is aware of one existing facility that plans to utilize reverse osmosis membrane filtration, with additional pretreatment steps to prevent membrane fouling.

Since produced water in the Permian basin contains significant quantities of salts, as well as pollutants such as ammonia that can be toxic to aquatic organisms, it is expected that technology used to treat Permian basin produced waters to discharge quality will be different than what is typically used for existing Subpart E dischargers in other basins. This is reflected in the pilot treatment systems that are being tested in the Permian and in the permit applications for these produced waters.

There are a number of pilot-scale treatment systems being tested on Permian Basin produced water. The EPA expects that data from these pilot projects will be available throughout 2025 and beyond.

The EPA identified research that indicates the potential for adverse environmental and health impacts (carcinogenic and non-carcinogenic) when aquatic organisms (e.g., fish, shellfish, and amphibians), terrestrial organisms (e.g., livestock and birds), and humans are exposed to produced water from the oil and gas extraction industry. While there are few studies that have evaluated these effects in current Subpart E discharges, the findings do reinforce the need for treatment of produced water prior to discharge to the environment.

In aquatic organisms, health impacts associated with exposure to produced water include changes in cardiac function, metabolic processes, hormone levels, cell viability, development, and immune function. For terrestrial organisms, health impacts associated with exposure include sudden death and reproductive, neurological, gastrointestinal, musculoskeletal, and upper respiratory issues, as well as hypothermia and drowning in birds.

In humans, exposure to produced water is associated with the increased risk of cancers, such as leukemia, lymphoma, and bladder cancer, and neurological, respiratory, vascular, dermatological, and gastrointestinal health issues, as well as birth defects in children.

The environment can be adversely impacted by produced water due to alterations in the composition and function of microbial communities in water and soil, reduced growth and bioaccumulation of toxins in crops, accumulation of toxins in soil and sediment, and soil sodification[1].

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[1] Sodification refers to a process where soil becomes saturated with sodium ions. The accumulation of sodium ions in soil impacts the soil's physical and chemical properties and can lead to a loss of soil fertility and reduced plant growth.

2. Existing Effluent Limitations Guidelines for Oil and Gas Extraction and Subpart E Requirements

2.1 Clean Water Act

Congress passed the Federal Water Pollution Control Act Amendments of 1972, also known as the Clean Water Act (CWA), to “restore and maintain the chemical, physical, and biological integrity of the Nation's waters.” 33 U.S.C. 1251(a). The CWA establishes a comprehensive program for protecting our nation's waters. Among its core provisions, the CWA prohibits the discharge of pollutants from a point source to waters of the United States (WOTUS), except as authorized under the CWA. Under section 402 of the CWA, discharges may be authorized through a National Pollutant Discharge Elimination System (NPDES) permit. The CWA also authorizes the EPA to establish nationally applicable, technology-based ELGs for discharges from different categories of point sources, such as industrial, commercial, and public sources.

Furthermore, the CWA authorizes the EPA to promulgate nationally applicable pretreatment standards that restrict pollutant discharges from facilities that discharge wastewater to WOTUS indirectly via publicly owned treatment works (POTWs), as outlined in CWA sections 307(b) and (c), 33 U.S.C. 1317(b) and (c). The EPA establishes national pretreatment standards for those pollutants in wastewater from indirect dischargers that may pass through, interfere with, or are otherwise incompatible with POTW operations. Pretreatment standards are designed to ensure that wastewaters from direct and indirect industrial dischargers are subject to similar levels of treatment. In addition, POTWs are required to implement treatment limitations applicable to their industrial indirect dischargers to satisfy any local requirements.

Direct dischargers (i.e., those discharging directly from a point source to surface waters rather than through POTWs) must comply with effluent limitations in NPDES permits. Discharges that flow through groundwater before reaching surface waters must also comply with effluent limitations in NPDES permits if those discharges are the “functional equivalent” of a direct discharge from a point source to a WOTUS. Indirect dischargers, who discharge through POTWs, must comply with pretreatment standards. Technology-based effluent limitations (TBELs) in NPDES permits are derived from ELGs (CWA sections 301 and 304, 33 U.S.C. 1311 and 1314) and new source performance standards (CWA section 306, 33 U.S.C. 1316) promulgated by the EPA, or based on best professional judgment (BPJ) where the EPA has not promulgated an applicable effluent guideline or new source performance standard (CWA section 402(a)(1)(B), 33 U.S.C. 1342(a)(1)(B); 40 CFR 125.3(c)). Additional limitations based on water quality standards are also required to be included in the permit in certain circumstances (CWA section 301(b)(1)(C), 33 U.S.C. 1311(b)(1)(C); 40 CFR 122.44(d)). The EPA establishes ELGs by regulation for categories of point source dischargers, and these ELGs are based on the degree of pollution control that can be achieved using various levels of pollution control technologies.

The EPA promulgates national ELGs for major industrial point source discharger categories for three classes of pollutants: (1) conventional pollutants (i.e., total suspended solids (TSS), oil and grease, biochemical oxygen demand (BOD_5), fecal coliform, and pH), as outlined in CWA section 304(a)(4) and 40 CFR 401.16; (2) toxic pollutants (e.g., toxic metals such as arsenic, mercury, selenium, and chromium; toxic organic pollutants such as benzene, benzo-a-pyrene, phenol, and naphthalene), as outlined in section 307(a) of the Act, 40 CFR 401.15 and 40 CFR part 423, appendix A; and (3) nonconventional pollutants, which are those pollutants that are not categorized as conventional or toxic (e.g., ammonia-nitrogen, per- and polyfluoroalkyl substances (PFAS), total dissolved solids (TDS)).

2.1.1 Types of ELGs

The EPA develops technology-based ELG regulations based on the performance of control and treatment technologies. The legislative history of CWA section 304(b), which is the heart of the ELG program, describes the need achieve higher levels of pollutant control through research and development of new processes, modifications, replacement of obsolete plants and processes, and other improvements in technology, while also accounting for the cost of pollutant controls. Legislative history and case law support that the EPA need not consider water quality impacts on individual water bodies as ELGs are developed.

There are many TBELs that may apply to a discharger under the CWA. As discussed below, there are four types of standards applicable to direct dischargers and two types of standards applicable to indirect dischargers.

2.1.1.1 Best Practicable Control Technology Currently Available

Traditionally, the EPA defines Best Practicable Control Technology (BPT) effluent limitations based on the average of the best performances of facilities within the industry, grouped to reflect various ages, sizes, processes, or other common characteristics. The EPA may promulgate BPT limitations for conventional, toxic, and nonconventional pollutants. In specifying BPT, the EPA considers several factors: the cost of achieving effluent reductions in relation to the effluent reduction benefits, the age of equipment and facilities, the processes employed, engineering aspects of the control technologies, any required process changes, non-water quality environmental impacts (including energy requirements), and such other factors as the Administrator deems appropriate. If, however, existing performance is uniformly inadequate, the EPA may establish limitations based on higher levels of control than what is currently in place in an industrial category, when based on an agency determination that the technology is available in another category or subcategory and can be practicably applied.

2.1.1.2 Best Available Technology Economically Achievable

The Best Available Technology (BAT) represents the second level of stringency for controlling the direct discharge of toxic and nonconventional pollutants. Courts have referred to this as the CWA's “gold standard” for controlling discharges from existing sources. In general, BAT represents the best available, economically achievable performance of facilities in the industrial subcategory or category. As the statutory phrase intends, the EPA considers the technological availability and the economic achievability when determining what level of pollution control represents BAT. Other statutory factors that the EPA considers in assessing BAT are the cost of achieving BAT effluent reductions, the age of equipment and facilities involved, the process employed, potential process changes, and non-water quality environmental impacts, including energy requirements, and such other factors as the Administrator deems appropriate. The Agency retains considerable discretion in assigning the weight to be accorded these factors. The EPA usually determines economic achievability based on the effect the cost of compliance with BAT limitations has on overall industry and subcategory financial conditions.

BAT reflects the highest performance in the industry and may reflect a higher level of performance than is currently being achieved based on technology transferred from a different subcategory or category, bench scale or pilot plant studies, or plants located in foreign countries. BAT may be based upon process changes or internal controls, even when these technologies are not common industry practice.

2.1.1.3 New Source Performance Standards

New Source Performance Standards (NSPS) reflect effluent reductions that are achievable based on the Best Available Demonstrated Control Technology (BADCT). Owners of new facilities have the opportunity to install the best and most efficient production processes and wastewater treatment technologies. As a result, NSPS should represent the most stringent pollutant controls attainable through the application of the BADCT for all pollutants (that is, conventional, nonconventional, and toxic pollutants). In establishing NSPS, the EPA is directed to take into consideration the cost of achieving the effluent reduction and any non-water quality environmental impacts and energy requirements.

2.1.1.4 Pretreatment Standards for Existing Sources

The CWA calls for the EPA to issue pretreatment standards for discharges of pollutants to POTWs. Pretreatment standards for existing sources (PSES) are designed to prevent the discharge of pollutants that pass through, interfere with, or are otherwise incompatible with the operation of POTWs. Categorical pretreatment standards are technology-based and are analogous to BPT and BAT; thus, the Agency typically considers the same factors in promulgating PSES as it considers in promulgating BAT. The General Pretreatment Regulations, which set forth the framework for the implementation of categorical pretreatment standards, are found at 40 CFR part 403. These regulations establish pretreatment standards that apply to all non-domestic dischargers.

2.1.1.5 Pretreatment Standards for New Sources

Section 307(c), 33 U.S.C. 1317(c), of the CWA calls for the EPA to promulgate Pretreatment Standards for New Sources (PSNS). Such pretreatment standards must prevent the discharge of any pollutant into a POTW that may interfere with, pass through, or may otherwise be incompatible with the POTW. The EPA promulgates PSNS based on BADCT for new sources. New indirect dischargers have the opportunity to incorporate into their facilities the BADCT. The Agency typically considers the same factors in promulgating PSNS as it considers in promulgating NSPS.

2.2 Oil and Gas Extraction Effluent Guidelines

The EPA first developed the oil and gas extraction effluent guidelines in the 1970’s. In 1979, regulations promulgating BPT limitations for the offshore (Subpart A), onshore (Subpart C), coastal (Subpart D) and agricultural and wildlife water use subcategories (Subpart E) were finalized (see 44 FR 22069, April 13, 1979). A 1993 amendment promulgated BAT, BCT and NSPS requirements for offshore facilities (see 58 FR 12454, March 4, 1993). In 1996, an amendment was published that added BAT, BCT, NSPS, PSES, PSNS, and revised BPT limitations for coastal facilities (see 61 FR 66086, December 16, 1996). A 2001 amendment added requirements for the discharge of synthetic-based drilling fluids and other non-aqueous drilling fluids in certain coastal and offshore waters (see 66 FR 6850, January 22, 2001). A 2016 rulemaking established pretreatment standards (PSES and PSNS) prohibiting the discharge of wastewater pollutants from unconventional oil and gas extraction facilities under Subpart C to POTWs (see 81 FR 41845, June 28, 2016).

There are three subcategories that apply to onshore activities (Subpart C, E, and F). The regulations at 40 CFR 435 Subpart C prohibit the discharge of wastewater pollutants from onshore facilities into navigable waters from any source associated with production, field exploration, drilling, well completion, or well treatment (i.e., produced water, drilling muds, drill cuttings, and produced sand). Standard practice in the industry for managing produced water from onshore activities is disposal via underground injection or re-use in the oil field for enhanced oil recovery, drilling or hydraulic fracturing. Some produced water from onshore facilities is also indirectly discharged via POTWs. Some is also used for dust suppression and road deicing.

The regulations at 40 CFR 435 Subpart E allow for discharge of produced water from onshore facilities into navigable waters west of the 98th meridian (see Figure 1) if the produced water is of good enough quality to be used for wildlife or livestock watering or other agricultural uses and the produced water is actually put to such use during periods of discharge (40 CFR 435.51). These facilities are engaged in the production, drilling, well completion, and well treatment in the oil and gas extraction industry. The Subpart E regulations contain a daily maximum BPT effluent limitation of 35 mg/L of oil and grease applicable to produced water. The Subpart E regulations do not contain BAT limitations for existing sources, and do not contain NSPS limitations for new sources. The Subpart E regulations also do not contain pretreatment standards for indirect discharge via POTWs.

Another subpart (Subpart F – Stripper Subcategory) applies to onshore facilities that produce 10 barrels per well per calendar day or less of crude oil and which are operating at the maximum feasible rate of production and in accordance with recognized conservation practices. These facilities are engaged in production, and well treatment in the oil and gas extraction industry. Subpart F does not contain effluent limitations. Any limitations are developed by the permitting authority on a case-by-case basis.

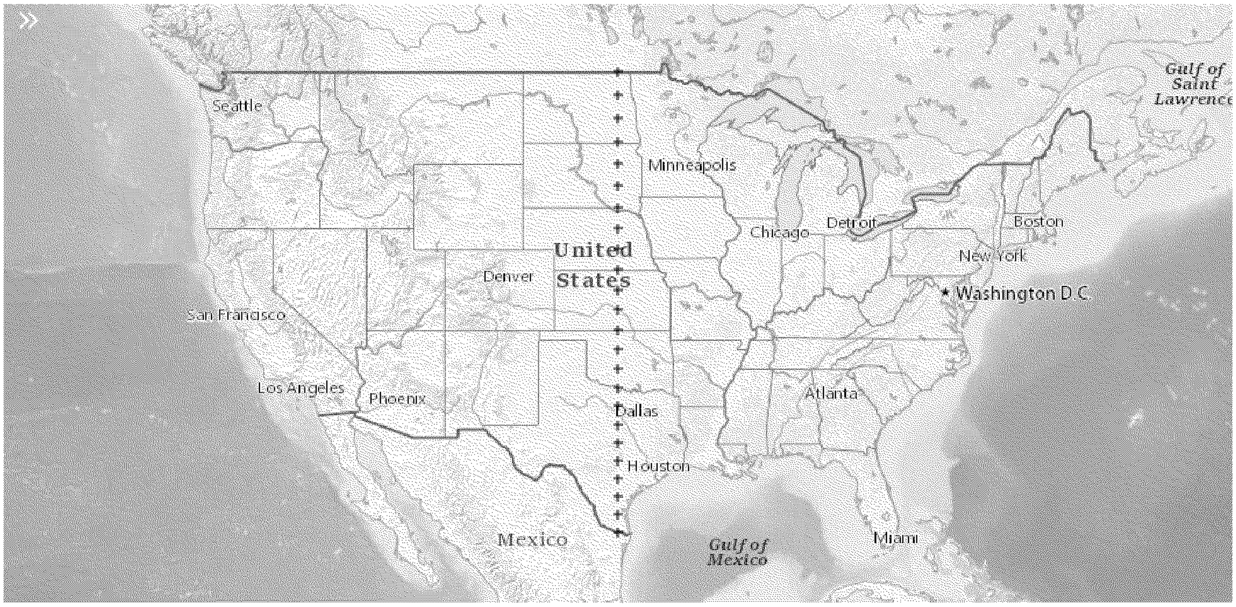

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Figure 1. Map of 98th Meridian

3. Industry Profile

3.1 Summary of Permits

All oil and gas operations west of the 98th Meridan can manage produced water under 40 CFR 435 Subpart E if the produced water has a use in agriculture or wildlife propagation and the produced water is actually put to such use during periods of discharge. Currently, all states with areas west of the 98th meridian except New Mexico are delegated to issue NPDES permits for oil and gas. However, the EPA only identified active permits issued for discharges under 40 CFR 435 Subpart E in California, Colorado, Texas, Utah, and Wyoming. From record reviews and discussions with state regulatory agencies, the EPA identified 176 active individual permits under Subpart E issued by primacy states. For Indian country and states that do not have primacy, the EPA issues the permits. From records reviews, the EPA identified 12 permits issued in Indian country. In many cases, there may be multiple discharge points/outfalls covered under a single permit. A February 4, 2025, search of the Integrated Compliance Information System (ICIS) database did not identify any active permits outside of California, Colorado, Texas, Utah and Wyoming. The State of Montana issues a general permit for produced water discharges, although not under Subpart E.

3.1.1 Description of State Issued Permits

The EPA reviewed all active Subpart E permits that it identified and summarized permit requirements such as regulated pollutants and chemical disclosure requirements and whether the permit requires whole effluent toxicity (WET) testing. The below summary is of permit requirements and does not incorporate any permit application requirements. Some additional states (Montana and New Mexico) that currently do not have Subpart E permits but have other relevant permitting information are summarized as well.

3.1.1.1 California

The NPDES Program has been delegated to the State of California for implementation through the State Water Resources Control Board (State Water Board) and the nine Regional Water Quality Control Boards (Regional Water Boards), collectively Water Boards. The EPA identified one active permit (CA0050628) issued to Sentinel Peak Resources California LLC. Segregation of flowback and chemical additive disclosure are not required, however, acute and chronic WET testing is required twice per year.

- **Segregation of Flowback**

Not addressed in the permit.

- **Chemical Additive Disclosure**

Not addressed in the permit.

- **WET**

Acute and Chronic Testing is required twice per year (see Table E-3 of the permit).

The permit states that: “Acute toxicity shall be assessed by the survival of aquatic organisms in 96-hour bioassays of undiluted waste and survival shall be no less than:

- 70 percent, minimum for any one bioassay; and
- 90 percent, median for any three consecutive bioassays.

There shall be no chronic toxicity in the effluent discharge.”

3.1.1.2 Colorado

NPDES permits in Colorado are issued by the Colorado Department of Public Health & Environment (CDPHE). CDPHE has both a General Permit and Individual Permits issued under 40 CFR Part 435 for discharges of produced water. There are six operators permitted under the General Permit and one Individual Permit issued under Subpart E.

General Permit Requirements

Segregation of flowback is not required, however, disclosure of chemical additives is required in the permit application. Acute and chronic WET testing is required quarterly.

- **Segregation of Flowback**

Segregation is not required. The permit instead states "Consistent with the scope of the oil and gas extraction point source category established by the EPA in the development of Federal Effluent Limitation Guidelines (ELGs), produced water discharges associated with production of crude petroleum and natural gas, drilling oil and gas wells, and oil and gas field exploration services are included within the scope of the permit. In addition to formation water, produced water may be commingled with injection water, any chemicals added downhole, chemicals added during the oil-water separation processes, or chemicals added during the treatment process."

- **Chemical Additive Disclosure**

The permit states that: "Chemicals that may be present in the discharge, whether added during exploration/production, or after the formation water has reached the surface of the well, will be provided in the permit application with each chemical's Material Safety Data Sheet (MSDS)."

- **WET**

The permit requires acute and chronic quarterly WET testing, however the Division has the authority to "vary the frequency as stated in the WET Policy."

CDPHE Individual Permit

Colorado has issued one individual permit (CO0000051) to POC-I, LLC. Segregation of flowback and disclosure of chemical additives is not required, but chronic WET testing is required monthly.

- **Segregation of Flowback**

Not addressed in the permit.

- **Chemical Additive Disclosure**

Not addressed in the permit.

- **WET**

The permit states that: "The permittee shall conduct the chronic WET test using *Ceriodaphnia dubia* and *Pimephales promelas*, as a static renewal 7-day test using three separate grab samples. The permittee shall conduct each chronic WET test in accordance with the 40 CFR Part 136 methods described in Short-term Methods for Estimating the Chronic Toxicity of Effluents and Receiving Water to Freshwater Organisms, Fourth Edition, October 2002 (EPA-821-R-02-013) or the most current edition."

3.1.1.3 Texas

Effective January 15, 2021, the onshore portion of oil and gas permitting became under the jurisdiction of TCEQ. The EPA identified one individual permit (TX0140153) that has been reissued by the Texas Commission on Environmental Quality (TCEQ) to Dorchester Operating Company, LLC. An additional eight permits have expired and are administratively continued or terminated. The EPA is also aware that as of early 2025, TCEQ has seven pending Texas Pollutant Discharge Elimination system (TPDES) permit applications for produced water discharges under Subpart E for operations in the Permian Basin.

For onshore permits in Texas, the EPA Region 6 requires at a minimum the following permit conditions:

- A reasonable potential analysis to evaluate the presence of toxic pollutants (127 priority pollutants).

- Screening for minerals such as chlorides, sulfates, and TDS are performed to determine whether a permit limit or further study of the receiving stream is required.
- Modeling (and monitoring) may also be performed for facilities that may negatively affect a water body's dissolved oxygen levels in receiving waters. Results are evaluated to determine what effluent limits are needed to maintain appropriate dissolved oxygen levels. Numerical models or other techniques are used to develop permit limits for oxygen-demanding constituents, in order to ensure the attainment of numerical criteria for dissolved oxygen.
- WET testing either acute or chronic depending on the permit writer's discretion.
- Monitoring and reporting requirements for other pollutants may also be performed to collect data that may be used to make informed decision during the next permit cycle.
- A letter of certification for the agricultural and wildlife use subcategory stating the beneficial use of the produced water.

- **Segregation of Flowback**

Not addressed in the permit.

- **Chemical Additive Disclosure**

Not addressed in the permit.

- **WET**

WET testing is required with the type (acute or chronic) up to the discretion of the permit writer.

3.1.1.4 Utah

Currently, the Utah Department of Water Quality has issued one Utah Pollutant Discharge Elimination System (UPDES) permit under Subpart E to Scout Energy Management LLC for its produced water discharge (UT0000035). Segregation of flowback and chemical additive disclosure are not required, however, chronic WET testing is required semi-annually.

- **Segregation of Flowback**

Not addressed in the permit.

- **Chemical Additive Disclosure**

Not addressed in the permit.

- **WET**

The permit states that: "Effective immediately, and lasting through the life of this permit, there shall be no acute or chronic toxicity in Outfall 001 as defined in *Part VI* and determined by test procedures described in *Part I. C.5.a* of this permit." Chronic WET testing is required semi-annually.

3.1.1.5 Wyoming

The Wyoming Department of Environmental Quality only issues individual permits under Subpart E for discharges. There is currently no general permit. The EPA identified 172 permits that that contain a total of 431 outfalls. Wyoming permits state that: "Development of permit limits involves considering all federal and state regulations and standards and incorporates the most stringent requirements into the permit. The effluent limits established in this permit are based upon Chapters 1 and 2 of the Wyoming Water Quality Rules and Regulations, 40 CFR Part 435 Subpart E, and other evaluations conducted by WDEQ related to this industry." Prohibition of flowback is required, however, disclosure of chemical additives is not required, and WET testing is not universally required.

- **Segregation of Flowback**

Wyoming permits state that permits do not cover activities associated with discharges of drilling fluids, acids, stimulation waters or other fluids derived from the drilling or completion of the wells.

- **Chemical Additive Disclosure**

Not addressed in permits.

- **WET**

Wyoming permits can have acute WET monitoring if the permit application reveals the permittee is using treatment formulations which may be toxic (e.g., flocculants, anti-scalants, antimicrobial compounds, etc.) or if they are near Class 2 waterbodies. Class 2 waterbodies are defined by Wyoming as those waters "known to support populations of fish and/or drinking water supplies and are considered to be high quality waters." WET monitoring and limits are implemented on Class 2 waters consistent with Wyoming's water quality standards regulations.

Additionally, some permit may remove previous WET testing if the permittee's compliance history indicates there is no toxicity (i.e., passing test results) or the produced water discharge and/or treatment chemicals have not changed.

3.1.1.6 Montana

The Montana Department of Environmental Quality permits all discharges of produced water under a state-issued, General Permit for Produced Water, Permit No. MTG310000 for discharges to state waters only (i.e., non-navigable waters). Therefore, these permits are not issued under Subpart E as the discharges do not discharge to navigable waters. As of January 2025, there were 30 operators issued authorization to discharge under this non-NPDES Produced Water Discharge Permit.

In the general permit, produced water is defined as "the water (brine) brought up from the hydrocarbon-bearing strata during the extraction of oil and gas, and may include formation water, injection water, and any chemicals added downhole or during the oil/water separation process."

Segregation of flowback and WET are not required, however, chemical additive disclosure and chemical and additive reporting are required.

- **Segregation of Flowback**

Not addressed in the permit.

- **Chemical Additive Disclosure**

The permit states that: "Applicants must disclose all chemicals and additives used at all leases and facilities that discharge produced wastewater: all product names, recommended uses, manufacturer, and Safety Data Sheets (SDSs). An SDS is acceptable for submission if it contains the information required above." The permit also states that: "The permittee shall submit to DEQ the list of all chemicals and additives used when submitting the [notice of intent] NOI; the volume of each liquid chemical and additive used; the mass of each solid chemical and additive used (if dissolved into a solution, provide the resulting solution concentration or ratio); and a list of the leases and facilities where the chemicals and additives are being used." In addition, the permit states: "The permittee shall submit to DEQ annually the Safety Data Sheets (SDSs) or Material Safety Data Sheets (MSDSs) for each chemical and/or additive used during the year."

- **WET**

Not addressed in the permit.

3.1.1.7 New Mexico

As of January 2025, there have not been any Subpart E permits issued in New Mexico. However, stakeholders have indicated that there is one application in development for discharge of produced water under Subpart E in New Mexico.

3.1.2 Description of Federally Issued Permits

The EPA issues Subpart E permits in Indian country when the Tribes do not have primacy. Currently, the EPA has 12 permits issued in Indian country.

3.1.2.1 EPA Region 8

The segregation of flowback is required, or disclosure of chemicals is required if segregation does not occur. Acute WET testing is required for 10 of the 11 permits. Chemical additives are not required to be disclosed universally.

Wind River Indian Reservation

On the Wind River Indian Reservation, EPA Region 8 currently has 10 Subpart E permits issued.

- **Segregation of Flowback and Chemical Inventory Reporting Requirement**

For permits requiring Chemical Inventory Reporting, the language states, "The Permittee shall maintain an inventory of the quantities and concentrations of the specific chemicals used to formulate well treatment and workover fluids (defined below). Unless these fluids are segregated, the Permittee shall submit the following information with the DMR, to the extent such information is obtainable after making reasonable inquiries to suppliers: all chemical additives in the well treatment or workover fluid, their trade names, purposes, supplier, CAS number, concentrations and amounts. The type of operation that generated the well treatment or well workover fluids shall also be reported. To the extent a Safety Data Sheet (SDS) contains the information required above, it may be submitted for purposes of complying with this provision. For purposes of this provision, well treatment and workover fluids will be considered segregated if the Permittee takes steps to recover a volume of fluid equivalent to the volume of the well treatment or workover fluid used in the job."

"'Well treatment fluids' means any fluid used to restore or improve productivity by chemically or physically altering hydrocarbon-bearing strata after a well has been drilled."

"'Well workover fluids' means salt solutions, weighted brines, polymers, or other specialty additives used in a producing well to allow for maintenance, repair or abandonment procedures."

- **Chemical Additive Disclosure**

Not addressed in the permits.

- **WET**

Acute WET testing is required in nine of 10.

Crow Indian Reservation

On the Crow Indian Reservation, EPA Region 8 has issued one Subpart E permit. This permit requires WET testing, segregation of flowback or chemical additive disclosure if segregation does not occur, per- and polyfluoroalkyl substances (PFAS) monitoring, and to report any changes in chemical additives from the time of permit development (i.e., chemical disclosure).

- **Segregation of Flowback**

The permit states that: "The Permittee shall maintain an inventory of the quantities and concentrations of the specific chemicals used to formulate well treatment and workover fluids (defined below). Unless these fluids are segregated, the Permittee shall submit the following information with the DMR, to the extent such information is obtainable after making reasonable inquiries to suppliers: all chemical additives in the well treatment or workover fluid, their trade names, purposes, supplier, CAS number, concentrations and amounts. The type of operation that generated the well treatment or well workover fluids shall also be reported. To the extent a Safety Data Sheet (SDS) contains the information required above, it may be submitted for purposes of complying with this provision. For purposes of this provision, well treatment and workover fluids will be considered segregated if the Permittee takes steps to recover a volume of fluid equivalent to the volume of the well treatment or workover fluid used in the job."

"'Well treatment fluids' means any fluid used to restore or improve productivity by chemically or physically altering hydrocarbon-bearing strata after a well has been drilled."

"'Well workover fluids' means salt solutions, weighted brines, polymers, or other specialty additives used in a producing well to allow for maintenance, repair or abandonment procedures."

- **Chemical Additive Disclosure**

The permittee must submit any changes to the chemical additives it submitted to the EPA when the permit was developed. If the permittee uses any additional chemicals from those disclosed above during the permit term, the permittee must submit notification of those additional chemicals to the EPA per the Planned Changes provision in Parts 8.1 and 8.1.1. of the permit.

- **WET**

Chronic WET is required in the permit.

3.1.2.2 EPA Region 9

Navajo Nation

EPA Region 9 has one permit issued in Navajo Nation that has two outfalls. Segregation of flowback, chemical additive disclosure, and WET testing are not required in the permit.

- **Segregation of Flowback**

Not addressed in the permit.

- **Chemical Additive Disclosure**

Not addressed in the permit.

- **WET**

Not required in the permit.

3.1.3 Variability across permits

The current regulation for discharges under Subpart E does not specify how permitting authorities should make a determination of 'good enough quality' to be used for wildlife or livestock watering or other agricultural uses. This has led to variability in the requirements of Subpart E permits among permitting authorities (i.e., states and EPA). The EPA has identified multiple factors that contribute to these variabilities, including but not limited to:

- Permit application data,
- The type of beneficial use (i.e., wildlife propagation or agriculture),
- Classification and water quality standards of receiving waters,
- Chemistry of source water for hydraulic fracturing, and
- Innate formation fluid quality.

EPA identified specific variability in how state permitting authorities permit the discharge of produced water, particularly related to the definition of produced water, produced water effluent limits, chemical additive disclosure, monitoring requirements (including PFAS and WET), and prohibition of discharge of flowback after hydraulic fracturing and maintenance processes.

Permit Limits

In Wyoming, water quality standards for produced water discharges are contained in every permit. For other permitting authorities, the water quality standards for the receiving water body are used to set produced water effluent limits and monitoring requirements. The only consistent requirement is an oil and grease effluent limitation and a requirement for a beneficial use. For instance, some permits require quarterly WET monitoring, whereas others require a one-time WET test or there is no WET test requirement. A large number of permits do not require screening for toxic pollutants, chemical disclosure, segregation of flowback or chemical additive disclosure after hydraulic fracturing, or monitoring for PFAS.

Additional Challenges

Permit applications do not require the disclosure of production wells that contribute to the produced water discharge. Many permittees have both underground injection wells and discharge permits to manage the produced water. From discussion with multiple operators, what method is used for disposal can vary over time for each production well. This creates a challenge in determining when flowback after hydraulic fracturing and maintenance processes could be discharged. Generally, there is no definition in permits of when flowback and maintenance activities ends (e.g., equal volume recovered as used in a hydraulic fracturing job). Therefore, there is potential for chemical additives from these operations to be present in produced water that is being discharged.

Another challenge permit writer's face is determining "good enough quality" for the agricultural and wildlife use. The EPA has developed a tool to aid permit writers in making these determinations (see https://www.epa.gov/eg/oil-and-gas-extraction-effluent-guidelines#bene-use-tool). However, there is a lack of data for constituents found in produced water related to crop health, ecotoxicology, livestock impacts, and other information that is necessary to make an adequate determination of "good enough quality."

In most cases, produced water that meets established water quality criteria for discharge often will contain an unpredictable and complex mixture of chemical additives and naturally occurring constituent for which no water quality standards and analytical methods exist. These concerns related to the unknown chemistry of produced water and the limited amount of data regarding treatability of produced water, particularly regarding reduction of toxicity, creates a challenge for regulators to determine treatment approaches and effectiveness. These knowledge gaps further complicate understanding treatment technology effectiveness to address potential human health and aquatic toxicity concerns resulting from discharges.

3.2 Company Information

There are many oil and gas producing basins located in the Western states. How produced water is managed depends on many factors, including the quality and quantity of produced water and the availability of management and disposal options. The EPA has not conducted a comprehensive evaluation of produced water generation and management for purposes of this report. However, a brief discussion is provided of some of the major basins, the companies operating in those basins, and produced water generation for select basins to provide perspective on factors that are important for the EPA's consideration of Subpart E regulations. For a comprehensive discussion of broader national produced water issues, see the reports prepared by the Ground Water Protection Council (GWPC, 2019 and GWPC, 2023).

3.2.1 Supermajor, Major, and Independent

Supermajor integrated oil and gas companies are defined as being involved in each segment of the industry and typically having market capitalization of $100 billion or more. Often, these are international companies. Major oil and gas companies are defined as typically having market capitalization of $10 billion to $100 billion. Whereas, independent companies focus on one segment of the industry and are defined as a producer who does not have more than $5 million in retail sales of oil and gas in a year or who does not refine more than an average of 75,000 barrels per day of crude oil during a given year.

3.2.2 Upstream, Midstream, and Downstream

Upstream companies focus on exploration and production. Globally, most crude oil production is controlled by National Oil Companies, which includes The Organization of Petroleum Exporting Countries (OPEC), or integrated international oil companies. Upstream companies benefit from high oil and gas prices and high volumes. Other metrics include rig count and capital spending. Midstream companies handle the transportation and storage of oil and gas. This segment is made up of many independent transportation operators. Oil and gas volumes are important to midstream companies, and prices as they relate to volume: if the price drops so low that upstream companies stop producing, midstream companies are not needed for transportation. Downstream companies manage the refining and marketing of oil and gas. There is lower market concentration in the downstream segment than the upstream segment. Downstream companies benefit from profit margins where they can sell their refined products for more than the cost of acquiring the crude resources. Other metrics include the number and size of refineries.

3.2.3 Oil and Gas Companies in Major Production Basins West of the 98th Meridian

According to the Institute for Energy Economics and Financial Analysis (IEEEFA), Enverus, and Rextag, the major oil and gas production basins west of the 98th meridian, and the major companies operating in those basins, include the following:

3.2.3.1 Permian

The Permian Basin is located in west Texas and southeastern New Mexico. Some of the major oil and gas companies with significant holdings in the Permian Basin include Chevron, ExxonMobil, Occidental Petroleum (Oxy), ConocoPhillips, Diamondback Energy, Apache, and Pioneer Natural Resources, with Chevron holding the largest percentage of acreage in the region. According to East Daley Analytics, the Permian Basin produced 6.1 million barrels per day of crude oil in 2023. The basin also produced 11.5 billion cubic feet per day of associated natural gas in 2023.

3.2.3.2 Williston

The Williston Basin includes areas in Montana, North Dakota and South Dakota. Some of the major oil and gas companies with significant holdings in the Williston Basin include Hess, ExxonMobil, EOG Resources, Continental Resources, Enerplus Resources USA, Hunt Oil and Whiting. The Williston Basin produced approximately 1.57 million barrels of oil equivalent per day in 2023. The Bakken Shale is the predominant source of oil and gas in the Williston Basin.

3.2.3.3 Denver-Julesburg

The Denver-Julesburg basin is located in northeastern Colorado and southeastern Wyoming. Major oil and gas holdings in the Denver-Julesburg (DJ) Basin include Oxy, Chevron and Civitas. Other majors include Bonanza Creek Energy, PDC Energy, EOG Resources and Whiting Petroleum. According to East Daley, the Denver-Julesberg produced approximately 0.630 million barrels of oil per day in 2023. Additionally, the U.S. Energy Information Administration estimated the production value closer to 0.670 million barrels of oil per day and 1.53 million barrels of oil equivalent per day in 2023.

3.3 Oil and Gas Production for Existing Subpart E Permittees

EPA collected data on oil and gas production for Subpart E permittees. The analysis was limited to Wyoming since the majority of existing Subpart E permits are located in that state. Wyoming is a major hydrocarbon producing state. Oil production has been steadily increasing in Wyoming over the past 20 years. While oil production was about 51.8 million BBLs in 2005, it increased to over 96 million BBLs in 2023. Gas production, on the other hand, has been steadily decreasing since 2009. After reaching a peak of over 2.5 billion Mcf, producers reported just over 1.2 billion Mcf of gas production to the Wyoming Oil and Gas Conservation Commission (WOGCC) in 2023 (see pipeline.wyo.gov for production data and graphs). The Wyoming State Geological Survey (January 2024) attributed the decrease in gas production to a lack of new gas wells being drilled and the declining rate of production from existing wells. The increase in oil production is attributed to new drilling activity, particularly in the Powder River Basin.

As part of an economic analysis to support development of ELGs, the EPA typically evaluates factors such as industry revenues and incremental costs to understand whether additional treatment is economically achievable for an industry consistent with the CWA statutory factors (see section 2 for more information). For studies, the EPA may conduct a screening-level analysis to understand the economics of a particular industry. For this study, the EPA conducted a screening-level analysis to determine oil and gas production (as a proxy for revenue) for companies with current Subpart E permits in Wyoming. The EPA obtained oil and gas production data from WOGCC (see pipeline.wyo.gov). The EPA used 2023 as an example year since this was the most recent full year of data available when the EPA began the study in 2024. The EPA then summed oil and gas production by company. This was done by cross-referencing the production data by company with active Subpart E permits[2] to obtain total production for each company in Wyoming that had an active NPDES permit in 2024. Some permittees were not found in the WOGCC production data, indicating that these companies may be engaged in other activities (such as water services or produced water treatment) or did not report any oil and production in 2023.

From this analysis, the EPA identified 82 companies that had 172 NPDES permits in Wyoming in 2024. Of these 82 companies, 74 reported nonzero oil production and 39 reported nonzero gas production in 2023. Total reported oil production in 2023 in Wyoming for these 74 companies was 20,518,911 BBL (about 21% of statewide oil production) and total reported gas production in 2023 in Wyoming for these 39 companies was 155,912,209 Mcf (about 13% of statewide gas production). The results of the EPA's analysis of oil and gas production for Wyoming Subpart E permittees can be found in Table 1.

Table 1. Reported Oil and Gas Production for NPDES Permittees in Wyoming in 2023

Company Name	Barrels Oil 2023	Mcf Gas 2023	Company Name	Barrels Oil 2023	Mcf Gas 2023
AETHON ENERGY OPERATING LLC	107,978	10,797,780	MEERKAT LOGISTICS AND OPERATIONS LLC	1,742	-
AMWEST PETROLEUM INC	N/A	N/A	MERIT ENERGY COMPANY	5,276,571	2,733,055
ANT HILLS PRODUCTION	2,137	-	MID-CON ENERGY OPERATING LLC	92,020	35,085
AntiCline Disposal, LLC	N/A	N/A	NEPECO	6,399	-
ANTLER ENERGY LLC	5,450	603,224	NEW ERA PETROLEUM INC	19,820	-
ARNELL OIL COMPANY	40,110	-	NEW HORIZON RESOURCES LLC	28,498	34,853
ATR ENERGY CORP	27,202	-	O'BRIEN ENERGY RESOURCES CORPORATION	14,384	-
BATAA OIL INC	6,240	2,343	OIL MOUNTAIN ENERGY INC	15,132	-
BEREN CORPORATION	15,186	-	OSAGE PARTNERS LLC	4,340	-
BIG MUDDY OPERATING LLC	46,635	-	OTT INC	4,120	-
BITTERROOT ENERGY PARTNERS LLC	4,399	3,335	PETROLEUM RESOURCE MANAGEMENT CORP	1,278	1,513
BLACK BEAR OIL CORPORATION	135,128	362,331	PETROX RESOURCES INC	32,746	-
BLACK GOLD SERVICES INC	18,514	3	PGC LLC	-	-

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[2] Note that in some cases there were differences in the name of companies reported in the WOGCC production data and the name of permittees contained in the WY DEQ permit data. In these cases, EPA used the company name from the WOGCC production data to prepare data summaries contained in this report.

Table 1. Reported Oil and Gas Production for NPDES Permittees in Wyoming in 2023

Company Name	Barrels Oil 2023	Mcf Gas 2023	Company Name	Barrels Oil 2023	Mcf Gas 2023
BLACK THUNDER OIL LLC	10,357	-	PINE HAVEN RESOURCES LLC	48,694	-
BREITBURN OPERATING L.P.	616,872	4,460,991	POC-I LLC	10,508	-
CARBON CREEK ENERGY LLC	-	58,826,907	PRINCIPLE PETROLEUM LLC	96,694	-
CAROL-HOLLY OIL CORPORATION	13,793	8,703	RANCH OIL COMPANY	29,899	-
CHAPMAN OIL COMPANY	3,109	-	RED TIGER OIL & GAS LLC	129,759	-
CITATION OIL & GAS CORPORATION	1,163,145	247,803	RICHARDSON OPERATING CO	96,920	399,247
CLOUD PEAK OPERATING LLC	8,850	-	SEEDY DRAW LLC	7,694	-
CODY ENERGY INC	4,173	103,578	SEP - Pass Creek, LLC	N/A	N/A
CONTANGO RESOURCES LLC	5,256,487	66,873,506	SHADCO	N/A	N/A
D90 ENERGY LLC	46,087	297,102	SIMON OIL LLC	40,071	-
DAUBE COMPANY THE	53,891	-	SIX BAR OIL LLC	60,625	-
DENBURY ONSHORE LLC	2,448,914	2,307,569	SOUTH PASS PETROLEUM INC	2,334	103,360
DIAMOND OIL & GAS LLC	17,489	158,608	SPELLBOUND ENERGY LLC	84,597	-
E & B NATURAL RESOURCES MANAGEMENT	271,432	1,026	SUNSHINE VALLEY PETROLEUM	111,784	374,979
ELLWOOD EXPLORATION LLC	20	-	TR OPERATING LLC	45,964	-
ENERGY EQUITY COMPANY	-	5,415	TRIBAR RESOURCES LLC	47,242	5,454
EVEREST OIL & GAS LLC	15,439	-	TRUE OIL LLC	1,107,795	1,110,202
GRANITE CREEK ENERGY LLC	205,772	7,141	UNDERWOOD OIL & GAS	580	-
HADLEY/JACKSON ENERGY LLC	14,384	-	USA ENERGY LLC	14,041	6,233
Homer Dean Oil Company	N/A	N/A	VALKYRIE OPERATING LLC	128,800	41,025
IRON CREEK PROPERTIES INC	2,877	12	VAQUERO BIG HORN LLC	338,217	-
J & J PRODUCTION LLC	1,846	-	VERMILION ENERGY USA LLC	975,831	3,868,331
JP OIL WYOMING LLC	43,888	67,519	VORTEX PETROLEUM INC	7,137	-
LOIL OIL LLC	70,099	150,503	WASHBURN LEE	1,339	-
M & K OIL COMPANY LLC	319,074	953,242	WESCO OPERATING INC	321,645	803,816
M2S OIL LLC	5,974	-	WESTERN AMERICAN RESOURCES LLC	18,075	32,676
MAXIM DRILLING & EXPL INC	14,325	81,306	WHITE ROCK OIL & GAS LLC	132,572	12,452
MAXIMUS OPERATING LTD	132,523	29,981	WYOIL CORP	13,245	-

Data from WOGCC production reports in 2023.
N/A means company was not found in WOGCC production data in 2023.
- Means that the company reported no production during the year.

4. Produced Water Characterization

4.1 Produced Water Volumes

The best source for data on volumes of produced water brought to the surface is the Ground Water Protection Council's Reports on Produced Water (GWPC, 2023). However, that data uses a 2021 baseline production year and is reported on a state-by-state basis. In addition, not all states require producers to report produced water generation, so developing national estimates pressents several challenges. Given continued growth in production in the Permian Basin, it is expected that current produced water volumes from Texas and New Mexico may be higher than the 2021 GWPC estimates. Given that most major production basins straddle state boundaries, a comparison of state production data is provided in Table 2 for selected states.

Table 2. Estimated Produced Water and Hydrocarbon Production in Select States (2021)

State	Number of Wells Producing	Volume of Produced Water Brought to Surface (bbl/year)	Volume of Hydrocarbon Produced
New Mexico	62,405	1,600,878,600	451,085,590 BBL 2,421,424 MMCF
North Dakota	18,163	643,154,596	405,127,827 BBL 1,075,538 MMCF
Oklahoma	48,492	1,744,894,591	148,337,393 BBL 2,544,913 MMCF
Texas	203,207	8,107,645,550	1,724,402,106 BBL 10,741,016 MMCF
Wyoming	27,171	1,559,881,944	85,290,133 BBL 1,081,393 MMCF

Source GWPC 2023

BBL = Barrel[3]; MCF = Thousand Cubic Feet[4]; MMCF = Thousand MCF

4.2 Discharge Volume Data

The EPA evaluated discharge monitoring reports (DMR) to determine reported discharge volumes by permittee for Wyoming discharges[5]. To resolve any potential reporting errors in DMRs that could reduce the accuracy of produced water discharge flow estimates, the EPA also performed a cross-check with NPDES permits and other documentation, such as inspection reports and permit quality reviews. The EPA then summed discharge volumes by company name. As an additional data quality check, the EPA also compared the company-level discharge volumes with the quantity of produced water reported to WOGCC as part of the production reports. This check helped identify any instances where reported discharge volumes exceeded produced water generation and allowed for additional adjustments to be made using other data sources. However, the EPA notes that these data may still contain inaccuracies and therefore should only be considered estimates of actual discharge volumes by company. Despite these limitations, however, this evaluation of discharges by permittee and by company can inform the evaluation of potential produced water treatment technology costs.

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[3] BBL = barrel, a unit of volume for oil and produced water, 42 gallons.

[4] A unit of natural gas production.

[5] Since little produced water is discharged under Subpart E in other states, the EPA limited this analysis only to Wyoming.

Table 3 presents the estimated average daily discharge (based on 2021, 2022 and 2023 DMRs), and the number of Subpart E permits held by the 82 companies identified in the EPA's analysis. Some permittees reported zero discharge during the reporting years, resulting in estimates of zero GPD for the average produced water discharge. The EPA estimated that daily produced water discharges in Wyoming for these 82 companies, based on DMRs, is approximately 39 million gallons per day (or approximately 935 thousand barrels per day). Based on WOGCC data, Wyoming producers reported generating approximately 1.63 billion barrels of produced water in 2023, which on average would be about 4.5 million barrels (187 million gallons) per day. Therefore, approximately 21% of produced water is discharged under Subpart E in Wyoming based on EPA's analysis.

Table 3. Estimated Subpart E Produced Water Discharge by Company in Wyoming

Company Name	Average Discharge (GPD)	Number of Subpart E NPDES Permits	Company Name	Average Discharge (GPD)	Number of Subpart E NPDES Permits
AETHON ENERGY OPERATING LLC	1,149,195	2	MEERKAT LOGISTICS AND OPERATIONS LLC	3,359	1
AMWEST PETROLEUM INC	0	1	MERIT ENERGY COMPANY	12,002,500	12
ANT HILLS PRODUCTION	7,028	1	MID-CON ENERGY OPERATING LLC	16,201	1
ANTICLINE DISPOSAL, LLC	0	1	NEPECO	37,389	1
ANTLER ENERGY LLC	8,000	2	NEW ERA PETROLEUM INC	110,844	1
ARNELL OIL COMPANY	32,222	2	NEW HORIZON RESOURCES LLC	170,000	1
ATR ENERGY CORP	16,250	1	O'BRIEN ENERGY RESOURCES CORPORATION	67	1
BATAA OIL INC	15,418	3	OIL MOUNTAIN ENERGY INC	110,500	1
BEREN CORPORATION	223,763	2	OSAGE PARTNERS LLC	0	4
BIG MUDDY OPERATING LLC	0	2	OTT INC	0	1
BITTERROOT ENERGY PARTNERS LLC	821	2	PETROLEUM RESOURCE MANAGEMENT CORP	17,278	1
BLACK BEAR OIL CORPORATION	244,844	4	PETROX RESOURCES INC	72,688	1
BLACK GOLD SERVICES INC	0	1	PGC LLC	0	1
BLACK THUNDER OIL LLC	191,580	3	PINE HAVEN RESOURCES LLC	994	3
BREITBURN OPERATING L.P.	3,484,006	6	POC-I LLC	4,214	4
CARBON CREEK ENERGY LLC	7,444	1	PRINCIPLE PETROLEUM LLC	1,081,282	5
CAROL-HOLLY OIL CORPORATION	23,394	3	RANCH OIL COMPANY	293,593	2
CHAPMAN OIL COMPANY	30,000	1	RED TIGER OIL & GAS LLC	0	1
CITATION OIL & GAS CORPORATION	5,145,556	5	RICHARDSON OPERATING CO	198,217	2
CLOUD PEAK OPERATING LLC	213,727	1	SEEDY DRAW LLC	0	1
CODY ENERGY INC	1,366	1	SEP - Pass Creek, LLC	27,031	1
CONTANGO RESOURCES LLC	3,054,977	9	SHADCO	0	1
D90 ENERGY LLC	630,271	2	SIMON OIL LLC	125,896	3

Table 3. Estimated Subpart E Produced Water Discharge by Company in Wyoming

Company Name	Average Discharge (GPD)	Number of Subpart E NPDES Permits	Company Name	Average Discharge (GPD)	Number of Subpart E NPDES Permits
DAUBE COMPANY THE	683,389	1	SIX BAR OIL LLC	7,703	1
DENBURY ONSHORE LLC	1,064,617	2	SOUTH PASS PETROLEUM INC	1,022	1
DIAMOND OIL & GAS LLC	166,250	1	SPELLBOUND ENERGY LLC	0	1
E & B NATURAL RESOURCES MANAGEMENT	50,472	3	SUNSHINE VALLEY PETROLEUM	21,202	1
ELLWOOD EXPLORATION LLC	7,933	1	TR OPERATING LLC	711,633	3
ENERGY EQUITY COMPANY	0	1	TRIBAR RESOURCES LLC	1,381,722	1
EVEREST OIL & GAS LLC	302,939	1	TRUE OIL LLC	27,417	1
GRANITE CREEK ENERGY LLC	949,289	1	UNDERWOOD OIL & GAS	0	1
HADLEY/JACKSON ENERGY LLC	44,667	2	USA ENERGY LLC	227,117	5
Homer Dean Oil Company	5,400	1	VALKYRIE OPERATING LLC	674,682	6
IRON CREEK PROPERTIES INC	30,000	1	VAQUERO BIG HORN LLC	3,362,222	6
J & J PRODUCTION LLC	8,222	1	VERMILION ENERGY USA LLC	0	2
JP OIL WYOMING LLC	222,000	2	VORTEX PETROLEUM INC	32,000	1
LOIL OIL LLC	110,000	2	WASHBURN LEE	0	1
M & K OIL COMPANY LLC	20,017	7	WESCO OPERATING INC	0	1
M2S OIL LLC	105,900	2	WESTERN AMERICAN RESOURCES LLC	17,640	1
MAXIM DRILLING & EXPL INC	0	1	WHITE ROCK OIL & GAS LLC	138,500	1
MAXIMUS OPERATING LTD	0	1	WYOIL CORP	126,561	1

Values are estimated based on Discharge Monitoring Reports
Zero values indicate that the permittee reported no discharge during the reporting years of 2021, 2022 and 2023.

4.3 Discharge Constituent Data

There are several sources of produced water quality data available. The EPA previously summarized national data on produced water characteristics (see USEPA, 2020) and therefore does not include a comprehensive evaluation of produced water characterization data in this report. Instead, the discussion presented here focuses on pollutants in existing Subpart E discharges based on DMRs. In addition, the EPA provides a summary of FracFocus disclosure data as an indicator of the constituents that may be found in produced water more broadly.

4.3.1 Discharge Monitoring Reports

The EPA retrieved DMR data for active permits in Wyoming to evaluate the concentration of various pollutants in reported discharges. As described above, the parameters regulated (and, therefore, monitored) in these permits vary; however, most DMRs contained data for chloride, oil and grease, and sulfide. Many DMRs also contained data for radium 226, total dissolved solids and sulfate. A select few DMRs also contained data for other pollutants. Figure 2 presents the DMR effluent data for the most commonly analyzed pollutants for the reporting years 2021 – 2023 for Wyoming Subpart E permittees.

The boxes present the 25th, 50th and 75th percentile concentrations and the whiskers present the minimum and maximum concentrations of all non-zero values for a given constituent.

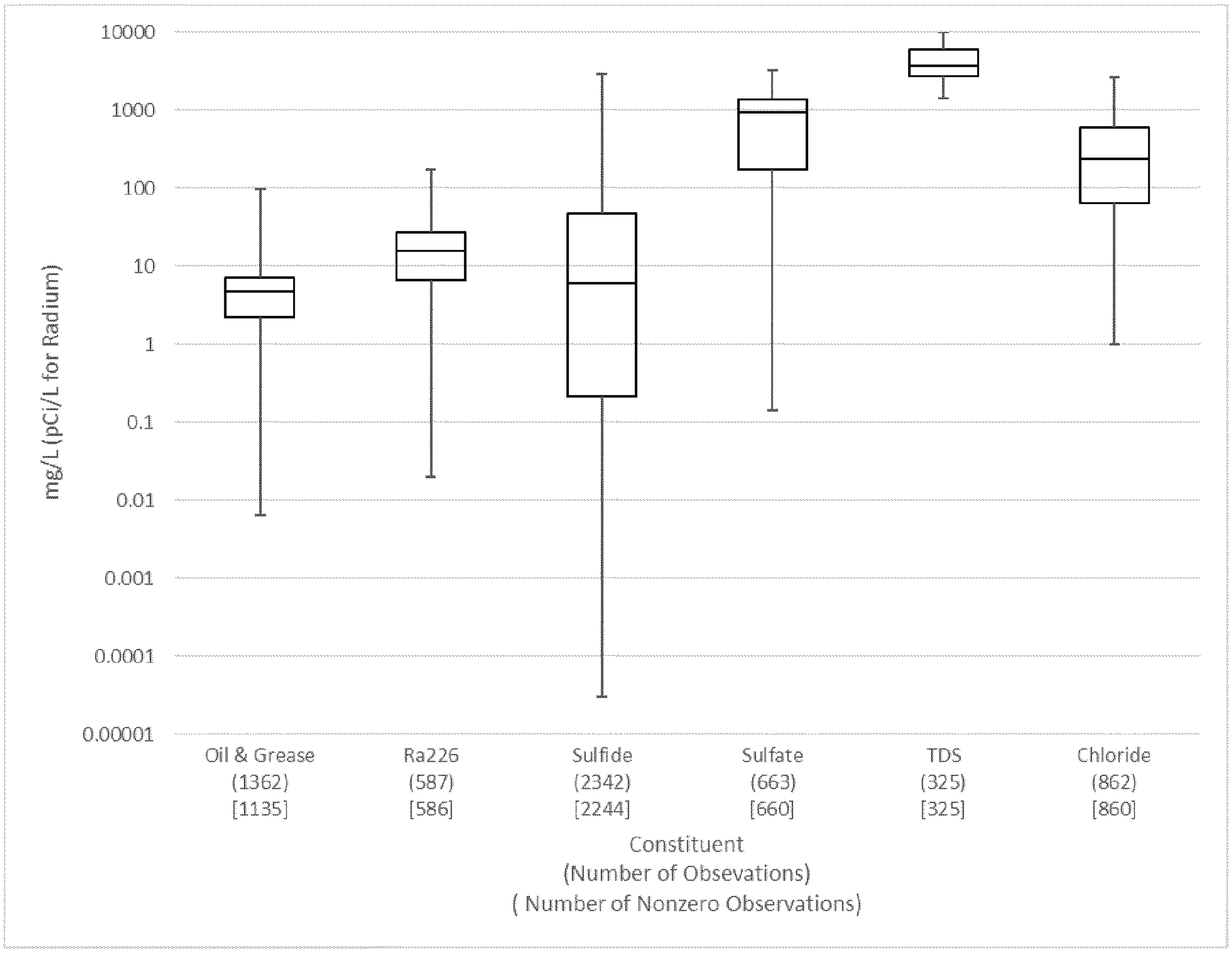

Figure 2. Constituent Concentrations in Wyoming Subpart E Discharges from DMRs (2021 – 2023)

4.3.2 FracFocus

The FracFocus Chemical Disclosure Registry (https://fracfocus.org/) is a publicly accessible online database managed by GWPC and the Interstate Oil and Gas Compact Commission (IOGCC). Oil and gas operators can use the database to disclose information about water and chemicals used in hydraulic fracturing fluids at individual wells, which is required in many states where oil and gas production occurs. Twenty-two states recommend or require such disclosures using FracFocus, with at least 17 states mandating them (Trickey et al., 2020). Each disclosure details several parameters about a given site: dates of operation, locational data, company/operator, well name, American Petroleum Institute (API) well number, vertical depths, base fluid volumes, and fluid composition. Fluid composition is further detailed by trade (product) name, supplier (manufacturer), purpose, compound name / Chemical Abstract Service (CAS) Registry Number, and relative percentage of total fluid (by mass). This provides regulators and the public with access to important information about well locations, operations, and chemical use.

However, certain limitations of the database may affect its use for regulatory, research, and public outreach efforts. Disclosure is not required by every state, limiting its coverage, and the information captured within each disclosure can vary, including the potential to withhold certain ingredient information. This is typically regarding proprietary business information and can include compound identifications, mass contributions, and functional purposes within the injection fluid. Maintenance chemicals (compounds used throughout the operation of a site after the initial stage) are also not disclosed, and disclosures do not reflect any redactions, corrections, or changes to formulations over time. Additionally, the database is provided as-is without quality-control procedures that promote data reliability (e.g., deduplication of records, cross-validation of chemical names and CAS numbers, or well location verification checks).

Table 4 aggregates and summarizes the disclosures from FracFocus databases through the open-source project Open-FF (https://open-ff.com/). Data was accessed January 27, 2025, and is presented as-is. The EPA has not linked actual FracFocus disclosures with specific Subpart E discharges as part of this study. However, the data on number of disclosures is informative for purposes of highlighting where hydraulic fracturing operations are occurring, and therefore where FracFocus disclosure data may provide information that will inform any future EPA actions.

Table 4. Number of FracFocus Disclosures by State

State	Number of Disclosures	State	Number of Disclosures
Texas	109,159	Montana	876
Colorado	20,340	Kansas	858
Oklahoma	18,839	Virginia	617
North Dakota	16,757	Alaska	264
New Mexico	13,522	Mississippi	171
Pennsylvania	11,140	Alabama	169
Wyoming	6,490	Kentucky	51
Utah	5,782	Michigan	31
Louisiana	4,372	Nebraska	14
California	3,769	Nevada	4
Ohio	3,502	Illinois	3
West Virginia	3,435	Indiana	2
Arkansas	2,870	Idaho	1

4.3.3 Reported Substances Used in Hydraulic Fracturing

Table 5 details a cross-walking of known substances reported to be used in hydraulic fracturing operations nationwide with lists of constituents in several federal and international sources (such as regulated pollutants or hazardous substances). The aggregated chemicals were assembled through the EPA's CompTox Chemicals Dashboard (https://comptox.epa.gov/dashboard/) from other existing lists of hydraulic fracturing chemicals[6] and in-progress research, deduplicated via unique DTXSID[7], and assigned to a new list denoted 'HFRLISTS'. This was then compared against other existing chemical lists that may indicate potential risks to human and/or ecological health. For each, a description of the cross-walking category and the number of applicable compounds is provided. Given that some categories may be subjective, narrowly focused, or depend on molecular structure, some categories may not fully represent

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[6] List codes for preexisting lists on Dashboard: EPAHFR, EPAHFRTABLE2, FRACFOCUS, CALWATERBDS

[7] Distributed Structure Searchable Toxicity substance identifiers (DTXSID) are unique substance identifiers, where a substance can be any single chemical, mixture, polymer, or chemical family.

the number of possible compounds and are presented for comparison purposes only. These results are aggregated for all production wells across the country and limited to data reported in the FracFocus database. The EPA did not attempt to correlate individual wells with Subpart E permits as part of the study. Therefore, for this study, the EPA did not determine which of these substances might be present in current (or future) Subpart E discharges. However, the evaluation characterizes classes of chemical compounds that might be present, and, therefore, might require treatment as part of any future regulatory revisions.

Table 5: Lists of Compounds Used Nationwide in Hydraulic Fracturing

Aggregate List Name	List Code	Description	Number of Compounds
40 CFR 355 Extremely Hazardous Substance List and Threshold Planning Quantities	40CFR355	Extremely Hazardous Substance List and Threshold Planning Quantities; Emergency Planning and Release Notification Requirements; Final Rule. (52 FR 13378)	41
Clean Water Act (CWA) Section 311(b)(2)(A) list	CWA311HS	Clean Water Act (CWA) Section 311(b)(2)(A) list of hazardous substances	106
Department of Homeland Security Chemicals of Interest	DHSCHEMS	Department of Homeland Security Chemicals of Interest: Appendix A to Part 27 of the Code of Federal Regulations (CFR)	57
EPA Regional Screening Levels Data Chemicals List	ORNLRSL	Chemicals associated with the Regional Screening Levels (RSLs) Generic Tables	300
EPA List of Hazardous Air Pollutants	EPAHAPS	Under the Clean Air Act, EPA is required to regulate emissions of hazardous air pollutants. This is the list of pollutants in the February 4, 2022, final rule	72
EPAECOTOX: Ecotoxicology knowledgebase version 6	ECOTOX_v6	Ecotoxicology knowledgebase (ECOTOX) is a comprehensive, publicly available knowledgebase providing single chemical environmental toxicity data on aquatic life, terrestrial plants and wildlife.	884
Health-Based Screening Levels for Evaluating Water-Quality Data	HBSL	Health-Based Screening Levels (HBSLs) are non-enforceable water-quality benchmarks	173
IARC: Group 1: Carcinogenic to humans	IARC1	This is the list of chemicals identified by the International Agency for Research on Cancer (IARC), in their monographs, as Carcinogenic to humans	16
IARC: Group 2A: Probably carcinogenic to humans	IARC2A	This is the list of chemicals identified by the International Agency for Research on Cancer (IARC), in their monographs, as Probably carcinogenic to humans	12

Table 5: Lists of Compounds Used Nationwide in Hydraulic Fracturing

Aggregate List Name	List Code	Description	Number of Compounds
IARC: Group 2B: Possibly carcinogenic to humans	IARC2B	This is the list of chemicals identified by the International Agency for Research on Cancer (IARC), in their monographs, as Possibly carcinogenic to humans	44
List of CERCLA Hazardous Substances (40 CFR 302)	40CFR302	List of CERCLA Hazardous Substances associated with 40 CFR 302	199
NIOSH: Immediately Dangerous to Life or Health Values	NIOSHIDLH	The immediately dangerous to life or health (IDLH) values are used by the National Institute for Occupational Safety and Health (NIOSH) as respirator selection criteria.	150
PFAS|EPA: PFAS structures in DSSTox (update August 2022)	PFASSTRUCTV5	List consists of all records with a structure assigned, and using a set of substructural filters and percent of fluorine in the molecular formula.	30
EPA PFAS chemicals without explicit structures v3	PFASDEV3	List of PFAS chemicals without explicit structures - polymers and other UVCB chemicals (Last Updated March 23rd, 2024)	2
Toxic Substances Control Act Reporting and Recordkeeping Requirements for Perfluoroalkyl and Polyfluoroalkyl Substances: Section 8(a)(7) Rule List of Chemicals	PFAS8a7	List of PFAS chemicals that meets the TSCA section 8(a)(7) rule structural definition of PFAS	26
State-Specific Water Quality Standards Effective under the Clean Water Act (CWA)	SSWQS	EPA has compiled state, territorial, and authorized tribal water quality standards that EPA has approved or are otherwise in effect for Clean Water Act purposes.	141
EPA: Chemical Contaminants - CCL 5	CCL5	The Contaminant Candidate List (CCL) is a list of contaminants that are known or anticipated to occur in public water systems. Version 5 is known as CCL 5.	18
EPA: Drinking Water Standard and Health Advisories Table	EPADWS	The EPA's Drinking Water Standard and Health Advisories Table summarizes EPA's drinking water regulations and health advisories, as well as reference dose (RFD) and cancer risk values, for drinking water contaminants.	81

5. Environmental Assessment

The EPA compiled information on what surface waters currently receive produced water discharges, the condition of those waters, and potential environmental and human health impacts associated with produced water. The results of EPA's research are discussed below.

5.1 Produced Water Discharges to Surface Water

5.1.1 Immediate Receiveing Waters of Produced Water Discharges

As discussed in further detail in section 3.1, most facilities currently discharging produced water under Subpart E are in Wyoming. Therefore, the EPA focused its data collection and mapping of surface waters on those receiving produced water discharges from facilities in Wyoming.

For these facilities, the EPA collected information from 2021-2023 DMRs on the receiving waters of produced water discharges, by facility and outfall. Receiving waters are reported in the DMR data by their common identifier (COMID).[8] The receiving waters were then mapped using the flowlines included in the United States Geological Survey (USGS)'s National Hydrography Dataset (NHD), which are differentiated by COMID. For some of the facilities, the COMID was not provided for the receiving waters. In these cases, the EPA determined the receiving water's COMID by first mapping the facilities' outfalls by their reported latitude and longitude in DMRs. The latitude and longitude points were then overlaid with the NHD receiving water data for relevant NHD regions in Wyoming to determine the receiving water COMID that each permit feature is within. The COMIDs for receiving waters containing outfalls were then also mapped using the flowline information from NHD. Figure 3 presents the flowlines (in blue) for receiving waters in Wyoming with produced water discharges. For additional context, Figure 3 also shows the location of the receiving waters within relevant NHD HUC10 watershed regions in Wyoming.

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[8] A COMID is a unique identification number used to delineate a specific segment of a surface water.

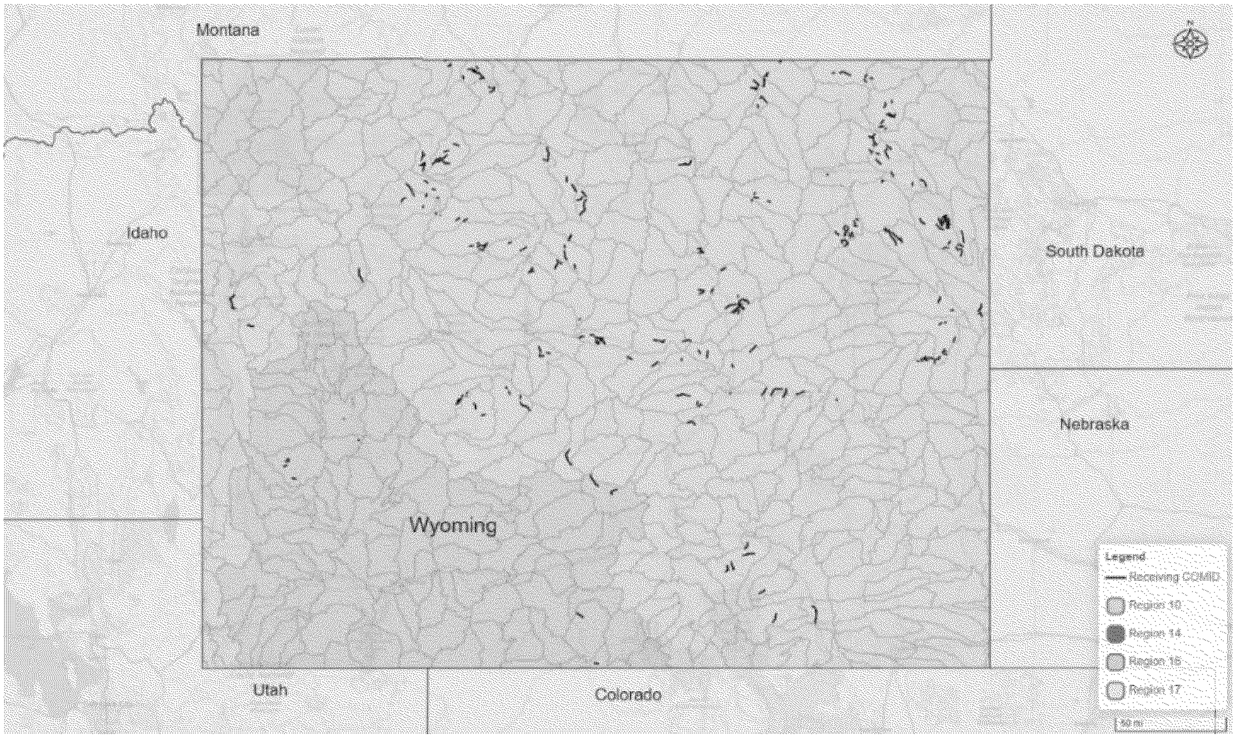

Figure 3. Receiving Waters Listed in DMRs with Discharges of Produced Water from Subpart E Oil and Gas Facilities in Wyoming

5.1.2 Impairment Status of Immediate Receiving Waters of Produced Water Discharges

Under section 303(d) of the CWA, surface waters that have been assessed by states as not meeting established water quality standards for their designated uses are listed as "impaired". Determining whether a surface water receiving produced water discharges from an oil and gas facility is listed as impaired is helpful for understanding which receiving waters may be most sensitive to pollution from these facilities.

To determine the impairment status of receiving waters with produced water discharges from oil and gas facilities in Wyoming (see section 5.2), the EPA used the EPA's Assessment, Total Maximum Daily Load (TMDL) Tracking and Implementation System (ATTAINS) spatial dataset to identify whether receiving waters with existing impairments overlapped with the receiving waters in Wyoming identified as receiving produced water discharges. For receiving waters where there was an identified overlap, the ATTAINS Assessment Attribute Summary Table provided information on the pollutant groups associated with the impairment. It is important to note that even if an immediate receiving water is not listed as impaired in ATTAINS, it does not mean there are no water quality issues. ATTAINS does not capture water quality issues for waterbodies in states that have not adopted the EPA's CWA section 304(a) aquatic life water quality criteria for pollutants of concern or that may not have the resources to comprehensively assess all waterbodies and/or a broad scope of pollutants. Additionally, several pollutants of concern in produced water (e.g., TDS, sulfate, etc.) do not have aquatic life criteria recommended by the EPA under the CWA section 304(a). Therefore, while the ATTAINS data is helpful for an initial screening level analysis of potential water quality issues in immediate receiving waters of produced water discharges for oil and gas facilities, additional information and analysis is needed to definitively determine whether immediate receiving waters without impairments have water quality issues.

Of a total of approximately 140 impacted immediate receiving waters, the EPA identified seven with 303(d) impairments. Four of the seven immediate receiving waters were identified as being impaired due to pathogens, one was listed for impairment due to sediments, and two were listed as impaired for multiple pollutant groups – oil and grease and toxic organics, and oil and grease and metals (other than mercury), respectively. As some of these contaminants (oil and grease, toxic organics, and metals) are found in produced water, the ATTAINS results suggest produced water discharges may be contributing to the impairment of these immediate receiving waters.

5.1.3 Environmental and Human Health Impacts Associated with Produced Water Discharges

The EPA's literature review identified research that indicates the potential for adverse environmental and human health impacts (carcinogenic and non-carcinogenic) when aquatic organisms (e.g., fish, shellfish, and amphibians), terrestrial organisms (e.g., livestock and birds), and humans are exposed to produced water from oil and gas operations. Additionally, the literature indicates that features of aquatic ecosystems (e.g., microbial communities and aquatic vegetation) and terrestrial ecosystems (e.g., crops, soil, and sediment) can be adversely impacted from exposure to produced water. The following sections discuss the evidence of adverse impacts for aquatic organisms and ecosystems (section 5.1.3.1), terrestrial organisms and ecosystems (section 5.1.3.2), and humans (section 5.1.3.3).

Due to a lack of research on impacts associated with Subpart E produced water discharges in Wyoming, the EPA relied on research – both observational and experimental - that analyzed impacts associated with exposure to produced water through other pathways (disposal pits, spills, or indirect discharges of produced water from CWT facilities to surface water) and in other areas of the United States and North America where oil and gas extraction occurs. Given that the chemical composition of produced water varies geographically and across facilities, the impacts to aquatic and terrestrial organisms and ecosystems and human health discussed in the research may differ from impacts associated with Subpart E produced water discharges in Wyoming. Due to this, the results discussed in this section are included in the report to provide an overview of the potential range of impacts associated with produced water exposure. As pollutants discussed in these studies overlap with pollutants in Subpart E discharges in Wyoming, or other areas of the United States where Subpart E discharges might occur in the future, these findings can inform decisions on risk management as Subpart E produced water discharges are considered.

5.1.3.1 Aquatic Organism and Ecosystem Impacts

The literature on impacts to aquatic organisms and ecosystems from produced water focuses on impacts to fish, shellfish, amphibians, aquatic vegetation, and microbes. The studies identified by the EPA are primarily experimental studies which evaluate changes in certain health outcomes (acute and/or chronic) in aquatic organisms and environmental outcomes after exposure to produced water occurs. The findings of these studies, organized by impacted group, are described here.

Impacts to Fish

Studies evaluating impacts to fish from exposure to produced water were primarily experimental studies that analyzed the potential toxicity of pollutants in produced water to various fish species through changes in specific health endpoints. Studies focused on impacts to rainbow trout[9] and zebrafish, as these are common model fish species. While the toxic effects of produced water exposure on fish were found to be chemical composition- and species-dependent, exposures to produced water were generally found to impact cardiac function, metabolic processes, hormone levels, and cell viability.

Rainbow Trout

Folkerts et al. (2023) analyzed impacts to later cardiac function and development in rainbow trout exposed *in ovo* at select critical points in cardiac development to differing dilutions of untreated produced water from the Devonian-aged Montney Formation in Alberta, Canada and lengths of time (acute versus chronic exposure). Cardiac development effects were measured in the juvenile rainbow trout approximately eight months post-fertilization through assessing fish swimming performance, aerobic scope, and cardiac structure. After eight months, rainbow trout exposed to a solution of five percent produced water for 48 hours (acute exposure), three days post-fertilization (dpf) or 10 dpf, experienced significantly reduced swimming performance and aerobic scope. When exposed to a solution of 2.5 percent produced water for 48 hours, rainbow trout exposed at three dpf also experienced significantly reduced swimming performance and aerobic scope, although rainbow trout exposed at 10 dpf did not experience as significant effects. In all acute treatments of produced water, changes in heart muscle tissue were observed in rainbow trout after approximately eight months, specifically decreases in compact myocardium thickness. Additionally, rainbow trout exposed to a solution of one percent produced water for 28 days (chronic exposure) showed similar cardiac function and developmental impacts observed for acute exposures.

Weinrauch et al. (2021) analyzed impacts to nutrient and metabolic dynamics in the liver in rainbow trout following acute exposure to diluted samples of untreated produced water from the Devonian-aged Montney Formation in Alberta, Canada. Immediately after a 48-hour exposure to a solution of 7.5 percent produced water, induction of xenobiotic metabolism[10], measured by ethoxyresorufin-O-deethylase (EROD) activity and abundance of mRNA cyp1a, increased by 8.8-fold and 10.3-fold, respectively. Three weeks post-exposure, these returned to baseline levels in the rainbow trout. After exposure to solutions of 2.5 percent and 7.5 percent produced water, the ability for cells in the liver to absorb glucose increased by 6.8-fold and 12.9-fold, respectively; the ability for cells in the liver to absorb alanine was variable after exposure to the solutions. These results indicated that aerobic metabolism was maintained in rainbow trout following exposure to produced water as well as the processing of glucose. Additionally, analyzed the synthesis of glucose in the liver following exposure to solutions of 2.5 percent and 7.5 percent produced water and found that gluconeogenesis decreased by approximately 30 percent immediately following exposure to the 2.5 percent produced water solution and decreased by approximately 20 percent three weeks after exposure to the 7.5 percent produced water solution. The ability for the liver to synthesize amino acids increased two-fold three weeks after exposure to the 7.5 percent produced water solution. Overall, this study indicated that exposure to produced water can alter

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[9] The EPA has an approved method for the use of rainbow trout to assess acute aquatic toxicity effects of pollution as part of WET testing (40 CFR 136.3). The EPA currently does not have an approved method for evaluating chronic aquatic toxicity effects using rainbow trout as part of WET testing. Therefore, chronic aquatic toxicity effects discussed in the literature are likely not covered by the results of the WET testing presented in the permits discussed in section 3.1.

[10] Induction of xenobiotic metabolism refers to the process by which certain enzymes involved in the metabolism of foreign substances are increased in response to exposure to various chemicals.

metabolism in the liver of rainbow trout, although homeostasis generally returns after three weeks post-exposure.

Additionally, an experimental study by Hu et al. (2022) examined impacts to cells (cell viability and damage to the cell plasma membrane) from rainbow trout after exposure to treated and untreated produced water samples from the Permian Basin. Cell lines were exposed to solutions between five and 50 percent whole produced water, produced water treated for organic compounds (produced water - inorganic fraction), and produced water treated for salts (produced water - salt control). After exposing cell lines to solutions of five to 10 percent whole produced water, produced water - inorganic fraction, and produced water - salt control, the authors observed no significant change in cell viability. A significant decrease in cell viability was observed after exposing cells to solutions of 20 to 50 percent whole produced water, produced water - inorganic fraction, and produced water - salt control, with whole produced water exhibiting the greatest toxicity to cells. For example, when exposed to solutions of 30 percent whole produced water, produced water - inorganic fraction, and produced water - salt control, cell viabilities were 26.9 percent, 43.1 percent, and 53.2 percent, respectively. The higher toxicity of whole produced water compared to produced water - inorganic fraction suggested that organic compounds in produced water had a stronger lethal effect on cell viability, although inorganic compounds likely also effected toxicity. Additionally, Hu et al. (2022) found that when cell lines were exposed to solutions of 50 percent whole produced water, produced water - inorganic fraction, and produced water - salt control, all resulted in cell viabilities of less than 10 percent. The authors concluded that these results showed that high salinity was the predominant driver of toxicity at 50 percent dilution of all three types of produced water. Similar trends were observed when analyzing whether exposure to produced water would cause damage of the cell plasma membrane in the rainbow trout cells.

Zebrafish

Folkerts et al. (2019) collected samples of untreated produced water from a single horizontal hydraulically fractured well from a basin in Alberta, Canada at different points in time in the production process (1.33, 72, and 228 hours post-well production onset) and conducted an experimental study to determine the toxicity of produced water to aquatic organisms, including early life-stage zebrafish and rainbow trout, and to determine whether toxicity was a function of when the produced water was generated in the production process. The analysis of the produced water samples showed that samples collected later in the production process had higher levels of inorganics (Cl, Na, Ca, K, and Mg ions and TDS), while samples collected earlier in the production process had higher levels of organics (polyethylene glycols [PEGs] and polycyclic aromatic hydrocarbons [PAHs]). Exposing the aquatic organisms to 30mL of the various produced water samples showed that toxicity was to a certain extent species-specific; zebrafish had lower lethality concentrations than rainbow trout. Although, trends in toxicity across the exposed aquatic organisms showed the samples of produced water from early in the production process had the highest toxic potential, indicating that in addition to high salinity, organics associated with produced water provide a significant contribution to toxicity in exposed aquatic organisms.

Another experimental study analyzed the potential acute and sublethal toxicity of suspended solids[11] in untreated produced water from the Devonian-aged Montney Basin in Alberta, Canada on early life-stage zebrafish (Lu et al., 2021). To study the acute toxicity, zebrafish embryos were exposed to suspended

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[11] The study used filtered suspended solids from six produced water samples collected from two hydraulic fracturing wells in Alberta, Canada (Lu et al., 2021). In the suspended solids samples, 10 of 16 parent polyaromatic hydrocarbons (PAHs), which are priority pollutants for the EPA, were detected; four alkyl PAHs were also frequently detected in the suspended solids samples (Lu et al., 2021).

solids from one to 96 hours post-fertilization (hpf). The assessment showed concentration-dependent acute toxicity to the embryos; significant correlations were found between mortality of exposed embryos and the concentration of suspended solids in produced water at three exposure concentration (12.5 mg/mL, 25 mg/mL, and 50 mg/mL), with 50 mg/mL suspended solids causing 100% mortality in the embryos. Sublethal toxicity was analyzed by exposing larval zebrafish to produced water sediment mixtures at two selected doses (1.6 and 3.1 mg/mL). At both doses, sublethal health effects observed in the larval zebrafish included increased EROD activity, as well as transcriptional alterations in xenobiotic biotransformation, antioxidant response, and hormone receptor signaling genes.

Impacts to Shellfish

The EPA identified one study that analyzed impacts to freshwater mussels from exposure to radium, strontium, and metals associated with legacy treated produced water discharges (originating from the Marcellus Basin) from a CWT facility to the Allegheny River (Pankratz and Warner, 2024). Samples of the streambed sediment, mussel soft tissue, and the mussel hard shell were collected upstream, at the CWT facility outfall, 0.5km downstream, and 5km downstream and tested for radium isotopes (^{226}Ra and ^{228}Ra). Samples of sediment, mussel soft tissue, and mussel hard shell collected at the CWT facility outfall did not have significantly different levels of radium isotopes compared to upstream samples, which the authors noted was likely due to previous remediation efforts at the outfall. Compared to samples collected upstream from the CWT facility outfall, levels of both radium isotopes were significantly greater in the sediment, mussel soft tissue, and hard-shell samples collected 0.5km downstream from the outfall. Compared to sampled upstream from the CWT facility outfall, mussel hard shells were found to have greater levels of ^{226}Ra up to five kilometers downstream of the CWT facility outfall. Analyzes were also performed on the mussel soft tissue and mussel hard shell to determine levels of strontium isotopes (^{87}Sr and ^{86}Sr) and heavy metals (cadmium). Pankratz and Warner (2024) found that the mussel soft tissue and hard shell ^{87}Sr/^{86}Sr ratios and the metal to calcium ratios (Na/Ca; K/Ca; and Mg/Ca) downstream of the CWT facility outfall were like those observed in produced water from the nearby Marcellus Basin. A similar conclusion was drawn from the analysis of the ^{228}Ra/^{226}Ra ratios in the mussel soft tissue and hard shell downstream of the CWT facility outfall. The findings of this study indicate the potential for retention in sediment and bioaccumulation in freshwater mussels of pollutants found in produced water. An experimental study conducted in 2021 also showed the potential for radium, strontium, and heavy metals like cadmium to accumulate in freshwater mussel soft tissue and concluded testing for the presence of these pollutants could be a biomonitoring tool to assess potential impacts from produced water discharges from oil and gas production (McDevitt et al., 2021).

Impacts to Amphibians

In addition to the Tornabene et al. (2023) study that analyzed changes in microbial community structure on amphibian skin from exposure to pollutants in produced water (discussed below), the EPA identified an experimental study analyzing changes in development and immune function in a species of frog (*Xenopus laevis*) after being exposed to pollutants associated with produced water (Robert et al., 2019). At three-weeks old, tadpoles were exposed for three weeks to a mixture of 23 pollutants associated with produced water that were diluted into their housing water. One group of tadpoles was exposed to a solution with a final concentration of 0.1 µg/mL of each constituent chemical and another group of tadpoles was exposed to a solution with a final concentration of 1 µg/mL of each constituent chemical. A third group of tadpoles was used as a control and exposed to a solution of 0.2 percent ethanol. Once the tadpoles completed metamorphosis and reached adulthood, the frogs exposed to the chemical mixture were assessed for potential developmental and immune impacts. Frogs exposed to the chemical mixture at both concentrations were not found to experience a significant increase in mortality or delay in metamorphosis compared to the control group, although the frogs did experience significantly decreased whole body weight at the end of metamorphosis when compared to the control group. Additionally, compared to the control group, frogs exposed to the chemical mixture at both concentrations experienced perturbation in immune homeostasis as evidenced by an observed decrease in the relative number of immune cells produced in the spleen, with the decrease being significant in frogs exposed to the 0.1µg/mL solution during development. Lastly, compared to the control group, frogs exposed to the chemical mixture at 1µg/mL exhibited weakened antiviral immune response given that they experienced increased viral load when infected by the ranavirus FV3. The findings of this study suggest that exposure of frogs in early life stages to chemicals in produced water can lead to long-term development and immune impacts.

Impacts to Aquatic Vegetation

Studies analyzing impacts of produced water on aquatic vegetation primarily focused on changes in growth for various species of algae. Hu et al. (2022) examined the potential toxicity, evaluated through measuring growth inhibition, of green microalgae (*Scenedesmus obliquus*) when exposed to whole produced water, produced water – inorganic fraction, and produced water – salt control from the Permian Basin. When exposed to each type of produced water at increasing fractions between five and 50 percent dilution, the growth inhibition rate of the green microalgae increased significantly, indicating a dose-response relationship. Hu et al. (2022) posited that the significant inhibition effect observed was likely due to increased salinity in the produced water samples, which caused irreversible damage to the green microalgae and resulted in the breakdown of cells. The authors also noted that exposure to produced water – salt control resulted in slightly higher toxicity to the green microalgae than exposure to whole produced water. For example, when exposed to solutions of 30 percent whole produced water and produced water – salt control, the growth inhibition rates were 68.4 percent and 72.9 percent, respectively. Hu et al. (2022) concluded that this was likely due to the high concentrations of ammonium present in the whole produced water compared to the produced water - salt control, which could promote algal growth and inhibit the adverse effects of whole produced water on the green microalgae. Additionally, when the green microalgae were exposed to solution of 30 percent whole produced water and produced water – inorganic fraction, the authors observed growth inhibition rates of 60.8 percent and 39.2 percent, respectively. Based on these results, the authors also concluded that organic compounds in whole produced water also have a significant effect on toxicity. This finding is like that of a study conducted by He et al. (2019), which observed an approximately 30 percent decrease in the growth inhibition rate of green microalgae once produced water had been treated to remove organics. Another study by Sambusiti et al. (2020) found that exposure to a synthetic produced water with various organic compounds and very low salinity was highly toxic to microalgae (*Pseudokirchneriella subcapitata*).

Microbial Impacts

Studies on microbial impacts primarily evaluated how exposure to produced water may change the structure and function of aquatic microbial communities. These studies observed associations between increases in pollutants associated with produced water in surface water and changes in microbial structure and function that can indicate potential changes in respiration, nutrient cycling, and markers of stress in aquatic ecosystems (Tornabene et al., 2023; Fahrenfeld et al., 2017). One other study focused on determining what pollutants in produced water may be most toxic to microbes in surface water, finding that salinity and organic compounds in produced water contributed significantly to toxicity (Hu et al., 2022).

Tornabene et al. (2023) analyzed changes in microbial community structure (in terms of phylotypes) in sediment, water, and on amphibian skin in wetlands in the Prairie Pothole Region of the U.S. (North Dakota and Montana) that are impacted by produced water from oil and gas production in the Williston Basin. The study primarily focused on the impacts of increases in chloride, strontium, and vanadium concentrations in wetlands associated with produced water. Tornabene et al. (2023) found that increases in chloride had minimal effect on the diversity and richness of the microbial communities in water and on amphibian skin; increases in chloride were associated only with differences in the structure of all three microbial communities and reduced microbial diversity of sediment communities. Stronger effects were generally observed between increases in heavy metals (strontium and vanadium) concentrations and the structure, richness, and diversity of microbial communities. Increases in strontium and vanadium were associated with increased differences in the structure of the three microbial communities. Increases in strontium concentrations were associated with decreased richness and diversity in the three microbial communities, while increases in vanadium concentrations were weakly associated with increased diversity in the three microbial communities. The authors concluded the association between vanadium concentrations and diversity was likely spurious given the concentrations of vanadium were much lower than strontium.

Fahrenfeld et al. (2017) also assessed changes in microbial community structure and function in water and sediment from exposure to pollutants associated with treated produced water from oil and gas operations in West Virginia. Water and sediment samples were collected from the upstream and downstream reaches of a stream running through a produced water disposal site, as well as from a control reach. Compared to the control reach, the water quality in the downstream reaches was characterized by increased conductivity, as well as two times the level of ions like chloride, ten times the level of sodium, and five to six times the level of barium. Given that these are contaminants associated with produced water, the authors determined the downstream sites to be impacted. Compared to the upstream and control reaches, impacted downstream reaches were found to have different microbial structures in both water and sediment communities that were unique to each site. Additionally, compared to the upstream and control reaches, changes in genes in the microbial communities were observed in the downstream reaches, particularly increases in dormancy, sporulation, methanogenic respiration, cadmium resistance, and genes related to stress responses (aromatic metabolism, sulfur metabolism, and nitrogen metabolism). Additionally, increases in antimicrobial resistance-related *arcB* and *maxB* genes in the microbial communities in the downstream reaches were observed, although the overall abundance of such genes did not increase. The authors noted antimicrobial resistance has been a concern with reports of the use of biocides in oil and gas operations.

Additionally, Hu et al. (2022) examined the impacts of treated and untreated produced water (bioluminescence inhibition) from the Permian Basin on a luminescent bacterium (*Vibirio fischeri*). Exposure to a solution of five to 10 percent whole produced water did not cause significant bioluminescence inhibition in the bacterium, indicating that water comprised of five to 10 percent whole produced water was not very toxic. For whole produced water, the bioluminescence inhibition level increased significantly when bacterium were exposed to solutions of 20 percent or more whole produced water. Hu et al. (2022) attributed this increase in toxicity to the increase in salinity of the solution. The major role of salinity in determining toxicity was confirmed when comparing the bioluminescence inhibition level of bacterium exposed to a solution of 20 percent whole produced water (38.6 percent) and the bioluminescence inhibition level of bacterium exposed to a solution of 20 percent produced water – salt control (33.2 percent). Hu et al. (2022) also found that organic compounds, particularly PAHs, in produced water may significantly contribute to acute toxicity of the bacterium as the bioluminescence inhibition level was higher for bacterium exposed to a solution of 20 percent whole produced water than for bacterium exposed to a solution of 20 percent produced water – inorganic fraction. Additionally, Hu et al. (2022) found that the bacterium experience a bioluminescence inhibition level of 85 percent when exposed to solutions with 40 percent whole produced water, produced water inorganic – fraction, and produced water – salt control, again indicating the significant role salinity plays in toxicity of produced water.

5.1.3.2 Terrestrial Organism and Ecosystem Impacts

The research on impacts to terrestrial organisms and ecosystems from produced water focuses on impacts to livestock (e.g. cattle), birds, crops, sediment, and soil. The studies identified by the EPA are a mix of observational and experimental studies which evaluate changes in certain health outcomes (acute and/or chronic) in livestock and birds and environmental outcomes for plants, sediment, and soil after exposure to produced water occurs. The findings of these studies are organized by impacted group.

Impacts to Livestock

The EPA's research into potential impacts to livestock resulted in identification of two observational studies which assessed impacts to livestock such as cattle, horses, sheep, llama, and chickens after exposure to produced water from oil and gas operations (Bamberger and Oswald, 2012; Bamberger and Oswald, 2015). These studies found that exposure to produced water was associated with increased incidence of health issues in livestock such as sudden death and reproductive, neurological, gastrointestinal, musculoskeletal, and upper respiratory issues, as well as increases in stillbirths among calves born to cattle exposed to produced water ((Bamberger and Oswald, 2012; Bamberger and Oswald, 2015).

Bamberger and Oswald (2012) conducted an observational study of health effects among livestock (cattle, horses, sheep, llama, and chickens) exposed to produced water from oil and gas operations in Colorado, Louisiana, New York, Ohio, Pennsylvania, and Texas. The most common exposure pathway for the livestock was through consumption of water from wells and/or springs and ponds or creeks contaminated by produced water. The health effects reported by farmers to the researchers primarily occurred among livestock located within one to three miles of oil and gas drilling operations. Health impacts reported from exposure to contaminated water for cattle included sudden death (usually within one to three days after exposure), reproductive issues, reduced milk production, neurological issues, inhibited growth, gastrointestinal issues, and upper respiratory issues. For bred cattle that were exposed to contaminated water, farmers reported increased incidence of stillborn calves with and without congenital abnormalities (e.g., cleft palate and white and blue eyes). In the few cases of stillborn births that could be diagnosed, veterinarians identified acute liver or kidney failure as the most common cause. Of the seven cattle farms Bamberger and Oswald (2012) studied in the most detail, they found that, on average, 50 percent of the herd was affected by sudden death and failure of survivors to breed after exposure. For the other livestock included in the study, health effects reported after exposure included neurological issues (horses and sheep), sudden death (chickens and sheep), gastrointestinal issues (horses), dermatological issues (chickens), upper respiratory issues (llama), and musculoskeletal issues (chickens and horses).

In another observational study conducted in 2015, Bamberger and Oswald assessed health effects among livestock (cattle, horses, chickens, and goats) exposed to produced water from oil and gas operations in

Pennsylvania, Colorado, Arkansas, North Dakota, and New York at initial exposure and then, on average, 25 months later. The purpose of the research was to determine changes in livestock health effects over long-term exposure and to assess whether changes in oil and gas operations (increase, no change, decrease) impacted health outcomes for livestock. All reported livestock health impacts were within two miles of an oil and gas operation. While livestock were exposed to produced water often through multiple pathways, like Bamberger and Oswald (2012), most exposures were associated with consumption of water from wells and/or springs and ponds or creeks contaminated with produced water. This exposure often continued after the initial interview, as most farmers were not able to switch livestock to an uncontaminated source of water. Additionally, like Bamberger and Oswald (2012), the most common health impacts reported in livestock following exposure were reproductive, neurological, gastrointestinal, respiratory, and growth issues, as well as reduced milk production. Changes in health impacts reported in livestock were analyzed, on average, 25 months after exposure. The study found that, in that timeframe, livestock exhibited a significant decrease in reproductive issues (although, farmers reported levels were still above normal), a significant increase in respiratory issues, and a significant increase in growth issues. Lastly, the results of Bamberger and Oswald's (2015) analysis of associations between changes in oil and gas drilling activity and changes in health issues among animals (livestock and companion animal [e.g., dogs and cats]) showed that: increases in activity were associated with non-significant increases in health issues; no changes in activity were associated with non-significant decrease in health issues; and decreases in activity were associated with significant decreases in health issues.

Impacts to Birds

The EPA identified one study from the U.S. Fish and Wildlife Service (USFWS) in 2014 that analyzed potential impacts to birds following exposure to produced water when it is stored in ponds prior to discharge. The study determined that exposure to produced water can cause deteriorated health and death in birds.

The study examined whether produced water from oil and gas operations could impact the health of migratory bird populations. The study primarily focused on characterizing produced water stored in evaporation ponds for removal of oil before discharge to surface waters at commercial and centralized oilfield wastewater disposal facilities (COWDFs)[12] in Wyoming (USFWS, 2014). While the produced water may be free of oil in the evaporation ponds, the water may still contain surfactants, geogenic chemicals, and chemicals added during the oil and gas extraction process, and may also be hypersaline, all of which can be hazardous to migratory bird populations that consume or come into physical contact with the produced water. Therefore, the USFWS collected water samples from 31 COWDFs receiving produced water between May 2009 and November 2012 to determine whether pollutants were present at levels known to be toxic to birds. The results of the water sampling campaign showed that surface tension (a way to measure the presence of surfactants) in all wastewater samples were above the threshold of 50 Dynes/cm which is associated with feather wetting in birds. Feather wetting causes feathers to become waterlogged, resulting in hypothermia, or loss of buoyancy which can cause birds to drown. Additionally, the wastewater was found to have high concentrations of chlorides, sulfates, and TDS. Concentrations of sodium in one COWDF were above 17,000 mg/L which is the threshold for sodium toxicity in birds. In four COWDFs, the water had TDS above 35,000 mg/L which classifies the water as hypersaline, which also indicates the potential for sodium toxicity in birds, as well as salt encrustation in their feathers. Lastly, in

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[12] Commercial disposal facilities are operated for profit and receive produced water from one or more oil and gas facilities, while centralized disposal facilities are owned and operated by the same oil and gas company that operates the wells that generate the produced water (USFWS, 2014).

wastewater samples, thresholds for toxicity to birds were exceeded for arsenic (1,000 µg/L), barium (10,000 µg/L), selenium (100 µg/L), and boron (5,000 µg/L).

Impacts to Crops

The EPA identified four studies that analyzed potential impacts to crops after irrigation with produced water. The findings of the studies indicate that irrigating crops with produced water can affect plant growth in terms of decreased rates of seed germination and reductions in biomass (Ben Ali et al., 2022; Miller et al., 2020; Sedlacko et al., 2020). Additionally, the studies found that irrigating crops with produced water is associated with diminished plant health, such as impaired photosynthesis, interruptions to cell signaling, interruptions to protein synthesis, impaired plant respiration, the accumulation of contaminants (e.g., heavy metals), and impaired metabolic function (Ben Ali et al., 2022; Sedlacko et al., 2020; Sedlacko et al., 2022).

Ben Ali et al. (2022) examined impacts on the growth of five types of crops, western wheatgrass, alfalfa, meadow bromegrass, Russian wildrye, and tall fescue when irrigated with desalinated produced water treated by reverse osmosis, raw produced water that had been diluted, raw produced water, and tap water from New Mexico. Ben Ali et al. (2022) observed that impacts to seed germination differed across species depending on their tolerance to various levels of saline water[13]; as salinity increased, the percentage of seeds that germinated for alfalfa, wheatgrass, bromegrass, and Russian wildrye decreased, with no seeds germinating when irrigated with raw produced water. Due to its higher tolerance to salinity, there was little change in the percentage of seeds that germinated for tall fescue as salinity increased, even when irrigated with raw produced water. Similar patterns were observed between increases in salinity and the amount of dry biomass for wheatgrass, bromegrass, Russian wildrye, alfalfa, and tall fescue, with irrigation with raw produced water resulting in plant death except for tall fescue. These findings are like those in a study conducted by Miller et al. (2020), which analyzed impacts to growth of wheat following irrigation with solutions of one percent and five percent untreated produced water from a well in the Denver-Julesburg Basin, a saltwater solution with salinity equivalent to the solution of five percent produced water, and control irrigation water. Miller et al. (2020) observed that with increased salinity of the irrigation water, wheat yields decreased, with the lowest yields observed for wheat irrigated with the saltwater solution and the solution of five percent produced water. Additionally, these findings are supported by a study conducted by Sedlacko et al. (2020) which examined impacts to growth of sunflower and wheat plants after irrigation with tap water, solutions of 10 percent and 50 percent raw produced water, solutions of 10 percent and 50 percent treated produced water using biologically active filtration followed by ultrafiltration (BAF-UF), and desalinated produced water using electrodialysis. The produced water was collected from the Niobrara formation of the Denver-Julesburg Basin. Sedlacko et al. (2020) observed that wheat and sunflower plants irrigated with solutions of 50 percent raw produced water and BAF-UF treated water displayed stunted growth, with reduced height and leaf area, and had reduced biomass compared to wheat and sunflower plants irrigated with the tap water control. Wheat and sunflower plants irrigated with solutions of 10 percent raw produced water, BAF-UF treated water, and electrodialysis treated water also resulted in decreases biomass, but to a lesser extent, indicating that salinity stress can affect plant growth.

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[13] The salinity – measured as mg/L of TDS - of the various types of water used for irrigation were: reverse osmosis desalinated water = 231 mg/L; tap water = 427 mg/L; diluted raw produced water = 1,400 mg/L; raw produced water = 8,610 mg/L (Ben Ali et al., 2022).

In terms of plant health, Ben Ali et al. (2022) observed that as salinity in the irrigation water increased, so did levels of sodium, calcium, magnesium, and chlorine, resulting in increased levels of these ions in plant tissues for all species, which the authors noted may be associated with observed decreases in biomass. Increases in magnesium ions were also associated with observed increases in chlorophyll content across the five plant species. In bromegrass and tall fescue, increases in sodium ions in plant tissue were associated in reductions in potassium ions. The uptake of potassium by plants is known to decrease with increasing sodium concentrations and is associated with interruptions to photosynthesis regulation in plants. Additionally, across all species, levels of manganese ions in the tissues decreased as the salinity of the irrigation water increased. Decreased manganese in plants tissues is associated with impaired photosynthesis. Across all species, Ben Ali et al. (2022) also observed decreases in phosphorous ions in plant tissues with increasing salinity of the irrigation water. Reductions in phosphorous ions in plants are associated with interruptions to cell signaling and protein synthesis. Reductions in zinc, iron, and sulfur, which are important for plant growth, plant respiration, chlorophyll content and protein synthesis, respectively, were observed across all species with increased salinity in the irrigation water, although a decline in plant growth was not observed with the decrease in zinc and iron. Boron ions were also observed to increase across the five plant species when they were irrigated with reverse osmosis desalinated water and raw produced water, although toxic impacts were not observed. Sedlacko et al. (2020) also observed changes in the ionome of wheat and sunflower plants that were exposed to solutions of treated and raw produced water. Even at the lower levels of exposure to solutions of raw produced water, BAF-UF treated water, and electrodialysis treated water, plants that were phenotypically similar showed changes in ionome composition in terms of heavy metals, salts, and micronutrients, which the authors suggested illustrates the impacts of irrigation with produced water on plant uptake, translocation, and accumulation of chemicals. Additionally, in a study conducted by Sedlacko et al. (2022), changes were observed in the metabolic function of wheat that was irrigated with diluted produced water from the Niobrara formation of the Denver-Julesburg Basin (10 percent and 50 percent solutions), independent of changes in metabolic function attributable to salinity stress when irrigated with a saltwater solution equal in salinity to the solution of 50 percent produced water. Specifically, the solutions of produced water were found to uniquely and significantly alter carbon, nitrogen, and lipid metabolism in wheat irrigated with the solutions. Wheat irrigated with the solution of 50 percent produced water experienced the most pronounced changes in metabolic function and impacts to survival, while wheat irrigated with the solution of 10 percent produced water exhibited some adaptive capacity to survive despite the produced water stressors. Based on these findings, Sedlacko et al. (2022) concluded that treatment of produced water, such as with nanofiltration or reverse osmosis, would likely be needed to reduce metabolic impacts, improving plant health.

Land Impacts

The EPA identified five studies that analyzed impacts to sediment and soil from the discharge, leaching, or application of produced water. Three of the studies focused on impacts to streambed sediment following the discharge of produced water from CWT facilities that handle wastewater from oil and gas production or from indirect contamination from leaching or spills at produced water disposal facilities. These studies found that produced water that enters a stream can alter the composition of constituents in the streambed sediment, increasing levels of salts, metals, and organic chemicals associated with produced water from oil and gas production or organic compounds unique to oil and gas production (Burgos et al., 2017; Van Sice et al., 2018; Orem et al., 2017). Two studies focused on impacts to soil after crops were irrigated with produced water. These studies found that even when crops are irrigated with low-saline produced water that has been blended with freshwater, constituents such as salt and boron can accumulate over the long-term in soils, increasing risks of soil sodification, groundwater salinization, and to plant health (Kondash et al, 2020; Miller et al., 2020).

Sediment

An observational study by Burgos et al. (2017) characterized contaminants in stream sediment between 10 to 19 km downstream of two CWT facilities that had previously discharged treated produced water from the Marcellus Shale formation in Western Pennsylvania. Burgos et al. (2017) found that sediment collected from layers corresponding to the years of maximum oil and gas production in the area contained elevated levels of salts, alkaline earth metals (strontium, radium, and barium), and organic chemicals (nonylphenol ethoxylates [NPEs] and PAHs). Additionally, researchers identified in these sediments' isotopic ratios of ^{226}Radium/^{228}Radium and ^{87}Strontium/^{86}Strontium which correspond to isotopes identified in the Marcellus Shale formation, suggesting the contaminants in the sediment likely were sourced from produced water from the Marcellus Shale formation. A study conducted by Van Sice et al. (2018) also looked at concentrations of radium in streambed sediment from the indirect discharge of Marcellus Shale formation treated produced water from five centralized waste treatment (CWT) facilities to downstream surface waters. The researchers collected sediment samples between 2011 and 2017 at locations within one and five kilometers from the point of discharge and within 58km downstream of the point of discharge. The authors found that over the period the sediment samples were collected, radium loadings to the stream decreased by approximately 95 percent, aligning with a 2011 voluntary request from the Pennsylvania Department of Environmental Protection that encouraged recycling of produced water, rather than treatment and discharge, from unconventional oil and gas operations. Despite this, the continued disposal of produced water from CWT facilities into the stream was associated with radium concentrations near the point of discharge that were often hundreds of times higher than background levels. For example, in 2014, near the point of discharge for two of the five CWT facilities, sediments were found to have radium concentrations of 15,000 ± 200 becquerel per kilogram (Bq/kg) and 24,600 ± 740 Bq/kg. Additionally, the researchers found that radium concentrations in sediments downstream of the point of discharge were 1.5 times higher than background concentrations.

Another study analyzed the composition of contaminants in stream sediment indirectly impacted (e.g., through leaching or spills) by produced water. Orem et al. (2017) analyzed streambed sediment samples collected from an unnamed tributary of Wolf Creek – near Fayetteville, West Virginia – upstream, downstream, and near an underground injection disposal facility that handles produced water from unconventional oil and gas operations in the Marcellus Shale formation. Unique to the sediments collected downstream of the disposal facility, the researchers found several organic compounds including diesel fuel hydrocarbons (e.g., pentacosane, Z-14-nonacosane) and halogenated hydrocarbons (e.g., 1-iodo-octadecane, octatriacontyl trifluoroacetate, dotriacontyl pentafluoropropionate), in addition to many chromatographically unresolved and unidentified hydrocarbons. This, the researchers suggested, indicated that produced water from the unconventional oil and gas operations had indirectly entered the stream and contaminants from the produced water were found in the sediment. The authors noted that in the sediment, concentrations of the various organic compounds derived from unconventional oil and gas operations were relatively low (less than 70 µg/L/g [dry weight]), and assays of human cell lines showed minimal effect when exposed to the sediment.

Soil

In parts of California, treated oilfield produced water is blended with freshwater and used to irrigate crops. An observational study conducted in the Cawelo Water District in Kern County, California analyzed impacts to soil quality from the use of blended produced water for irrigation of crops (Kondash et al., 2020). Soil samples were collected from a field where hay was spray irrigated with produced water after it was treated for oil and sites where crops were drip irrigated using produced water blended with freshwater or local groundwater, and subsequently analyzed to quantify the concentration of salts, metals, radionucleides (^{226}Radium and ^{228}Radium), and dissolved organic carbon. The researchers found that, while none of the water quality parameters studied exceeded the current California irrigation quality guidelines in the blended produced water, soils irrigated with the blended produced water had higher concentrations of salts and boron compared to soil from crops irrigated with groundwater. This suggested that while blended produced water may be low in salts and boron when they are applied, long-term accumulation may occur in the soils its applied to which can result in long-term risks to soil sodification, groundwater salinization, and plant health from boron toxicity. Miller et al. (2020) also found accumulation of salts in soil when crops are irrigated with produced water and associated this with diminished plant health. While soils irrigated with unblended produced water and blended produced water contained ^{226}Radium, ^{228}Radium, and dissolved organic carbon, the concentrations were not significantly different from soil irrigated with groundwater (Kondash et al., 2020).

5.1.3.3 Human Health Impacts

Through the literature review, the EPA identified research indicating potential adverse carcinogenic and non-carcinogenic human health impacts associated with produced water from oil and gas operations. The two major exposure pathways studied for human contact with pollutants in produced water are through consumption of contaminated drinking water and inhalation of chemicals in produced water, such as volatile organic compounds (VOCs), which is supported by a review of the literature conducted by Werner et al. (2015). While studies on human health impacts from exposure to produced water are limited, the studies the EPA found analyzed the potential for adverse human health impacts through inference when chemicals that are well-known human hazards were identified in drinking water or air around produced water disposal areas, and through experimental studies that analyzed non-carcinogenic and carcinogenic health impacts when humans had come into contact with produced water or when human cells and laboratory animals were exposed to produced water. The findings of the research are organized by exposure pathway.

Water

Research has shown the potential for adverse health effects to occur in humans exposed to produced water through consumption of contaminated drinking water. This research includes studies that evaluate changes in risk or the incidence of adverse health impacts associated with exposure to produced water from drinking water consumption, as well as studies that analyze the presence of pollutants in drinking water contaminated with produced water that are known to cause adverse human health impacts.

To evaluate changes in risk, an observational study was conducted by Gaughan et al. (2023) to analyze associations between exposure to pollutants in produced water and certain birth defects. The study focused on infants born in Ohio from 2010 to 2017, corresponding to a period in which natural gas production increased in Ohio by 30 percent. Of the 965,236 live births in Ohio during that period, 4,653 infants were born with birth defects. For the infants born with birth defects, the researchers estimated exposure to pollutants from oil and gas operations based on maternal residential proximity at birth to active oil and gas wells and using a metric specific to the drinking water exposure pathway that identified oil and gas wells hydrologically connected to a residence. The researchers found that the odds an infant would be born with any birth defect were, on average, 1.13 times higher in infants born to mothers living within 10 km of an oil and gas well compared to infants born to unexposed mothers. The odds of an infant being born with any birth defect were, on average, 1.3 times higher in infants born to mothers living in a residence hydrologically connected to an oil and gas well compared to mothers living in hydrologically unconnected residences. When analyzing the odds of an infant being born with a specific birth defect, Gaughan et al. (2023) found that, on average, the odds were elevated that an infant would be born with neural tube defects (1.57 times higher), limb reduction defects (1.99 times higher), and spina bifida (1.93 times higher) if the infants were born to mothers living within 10 km of an oil and gas well compared to infants born to unexposed mothers.

Additionally, Nagel et al. (2020) conducted a review of experimental studies evaluating the potential for endocrine-mediated health impacts in humans from exposure to a mixture of 23 chemicals commonly found in produced water from oil and gas operations. All studies reviewed used the same mixture of chemicals at four environmentally relevant doses (0.01 mg/L mix, 0.1 mg/L mix, 1 mg/L mix, and 10 mg/L mix) that represent concentrations of chemical found in surface water and groundwater in areas with dense oil and gas operations and concentrations found in the produced water itself. In all studies, the mixtures were comprised of the 23 chemicals in equal ratios. Additionally, all the studies look at in vivo impacts to either laboratory mice and tadpoles or human tissue culture cells. In general, the various mixtures of chemicals found in produced water exhibited potent antagonistic activity for the estrogen, androgen, glucocorticoid, progesterone, and thyroid receptor when they were applied to the human tissue culture cells. The researchers also administered the mixtures via drinking water to pregnant mice and to tadpoles to determine how they might impact reproductive and developmental health. Developmental exposure to the mixtures substantially impacted pituitary hormone concentrations, reduced sperm counts, altered folliculogenesis, and increased mammary gland ductal density and preneoplastic lesions in mice (Nagel et al., 2020). Additionally, exposure to the mixtures resulted in altered energy expenditure, exploratory and risk-taking behavior, and impairments to the immune system of mice, while frogs experienced altered basal and antiviral immunity (Nagel et al., 2020).

To evaluate the presence of chemicals in produced water that are associated with adverse health impacts if consumed, Elliott et al. (2016) reviewed the potential for carcinogenic effects, particularly for risks of childhood leukemia and lymphoma, from exposure to pollutants in produced water from oil and gas drilling operations. Elliott et al. (2016) collected a list of 1,177 chemicals found in hydraulic fracturing fluid and wastewater from the EPA and assessed their carcinogenicity and potential for increased risk of leukemia and lymphoma using monographs from the International Agency for Research on Cancer (IARC). More than 80 percent of pollutants on the list were not evaluated by IARC, but Elliott et al. (2016) identified 111 water pollutants evaluated by IARC, 49 of which were identified as known, probably, or possible human carcinogens. Additionally, 17 water pollutants have evidence supporting an association with an increased risk or leukemia or lymphoma, such as petroleum-related VOCs (e.g., benzene), metals (e.g., cadmium), solvents (e.g., dichloromethane and tetrachloroethylene), and PAHs (benzo[b]fluoranthene, dibenz[a,h]anthracene, and benzo[k]fluoranthene).

Landis et al. (2016) and Abraham et al. (2023) conducted experimental studies to quantify levels of disinfection byproducts (DBPs) in drinking water impacted by produced water from oil and gas operations. The generation of DBPs at drinking water treatment systems downstream of oil and gas operations is a public health concern as epidemiological studies have shown that exposure to DBPs through consumption of drinking water is associated with increased risk of bladder cancer, miscarriage, and birth defects in humans (Abraham et al., 2023). Elevated bromide and iodide levels in water sourced for drinking water is one way for DBPs, in this case, brominated DBPs and iodinated DBPs, to appear in drinking water as conventional drinking water treatment processes do not remove bromide or iodide before the water is disinfected through chlorination of chloramination processes. In 2012, the EPA collected water samples from the Allegheny River in Pennsylvania at six sites downstream of a commercial wastewater treatment facility (CWTF) that solely treats produced water from oil and gas producers and impacts two public drinking water systems. The results of the sampling campaign showed that discharges from the CWTF were associated with significant increases (39 ppb, 53 percent) in bromide concentrations at public drinking water system intakes downstream compared to the upstream reference values during periods of low river discharge (Landis et al., 2016). While high river discharges resulted in lower absolute concentrations due to increased dilution capacity, samples taken at the nearest downstream public drinking water system continued to show bromide concentrations that were above upstream levels (7 ppb, 22 percent). With these bromide concentrations at drinking water intakes, Landis et al. (2016) estimated modeled increases in total trihalomethanes (THM) of three percent and positive shifts of between 41 to 47 percent to more toxic brominated THM. In an experimental study, Abraham et al. (2023) simulated surface water impacted by produced water by diluting produced water generated in Texas 100-fold with raw river water, resulting in a mixture with bromide concentrations approximately three times greater than average levels of natural bromide found in surface water. The mixtures were then treated using chlorination and chloramination processes and levels of brominated DBPs and iodinated DBPs were compared to raw river water. Under both treatment processes, water impacted by produced water generated 1.3 to five times more total DBPs compared to the raw river water, with individual DBPs ranging from less than 0.1 to 122 µg/L. Chlorinated waters were found to form the highest levels of DBPs, including brominated THM exceeding the EPA's regulatory limit of 80 µg/L. Chloroaminated waters generated more iodinated DBPs and the highest levels of haloacetamides in water impacted by produced water. Additionally, water impacted by produced water that was treated through chlorination or chloramination had higher estimated cytotoxicity and genotoxicity than raw river water that was treated, with chloroaminated water impacted by produced water having the highest estimated cytotoxicity due to having higher levels of iodinated DBPs and haloacetamindes which are more toxic than brominated DBPs.

Air

Humans may be exposed to pollutants in produced water through inhalation when compounds in the produced water, like PAHs, are volatized during the disposal process (Moore et al. 2014). In their 2016 study, Elliott et al. identified 29 air pollutants evaluated by the IARC, 20 of which were identified as known, probably, or possible human carcinogens. Of the 20 pollutants, 11 had evidence of increased risk for leukemia or lymphoma, such as 1,3-butadiene, benzene, formaldehyde, dibenz[a,h]anthracene, tetrachloroethylene, and PAHs. Ma et al. (2022) analyzed the non-carcinogenic and carcinogenic risks to human health from produced water during the disposal process. They focused on analyzing scenarios where produced waters are stored in tanks and/or ponds and leaks occur. In estimating the non-carcinogenic and carcinogenic risks for inhalation exposure from contaminated soil when leakages occur, Ma et al. (2022) found that when exposed to compounds like VOCs (e.g., benzene) both risks increased rapidly over time in all scenarios (after 10 days, 100 days, 1,000 days, and 10,000 days of leakage), regardless of recharge rates, causing risk estimates to exceed stipulated thresholds by several orders of magnitude. Ma et al. (2022) concluded that the results support that the inhalation pathway may pose the greatest risk to human health with respect to VOCs in produced water that are more easily transferred into the air.

Multiple Exposure Pathways

Humans can experience adverse health impacts associated with exposure to produced water through multiple exposure pathways. As previously discussed, Bamberger and Oswald (2012) conducted an observational study tracking the incidence of adverse health impacts among farmers in six states with farms within one to three miles of an oil and gas drilling operation. Human exposure in the study mostly occurred through using well or spring water that was contaminated with produced water for drinking, cooking, showering, and bathing (Bamberger and Oswald, 2012). After using the water, farmers reported to Bamberger and Oswald (2012) that they experienced adverse health impacts such as upper respiratory issues (burning of the nose and throat), burning of the eyes, headache, gastrointestinal issues (vomiting and diarrhea), dermatological issues (rash), and vascular issues (nosebleeds). In 2015, Bamberger and Oswald conducted a longitudinal observational study that tracked the changes in health impacts among farmers in six states with farms within two miles of an oil and gas drilling operation. Changes in health impacts were tracked over 25 months and were analyzed along with changes in oil and gas drilling operations in the area (Bamberger and Oswald, 2015). Human exposure in the study mostly occurred through exposure to water from well or spring water, as well as pond or creek water, that was contaminated with produced water or through exposure to air pollution from the oil and gas drilling operations (Bamberger and Oswald, 2015). The most common adverse health impacts reported by farmers were neurological issues (headache, dizziness, difficulty concentrating, short-term memory loss, skin numbness and tingling, incoordination, seizures, and inability to stand), respiratory issues (burning in the nose and throat, coughing, wheezing, difficulty breathing, and asthma), vascular issues (nosebleeds, stroke), dermatological issues (hair loss and rashes), and gastrointestinal issues (vomiting, diarrhea, cramping, weight loss, and weight gain), with no significant change in health issues over the 25 months (Bamberger and Oswald, 2015). When changes in health impacts were analyzed with changes in oil and gas drilling operations over the 25 months, Bamberger and Oswald (2015) found that: in areas where industrial activity increased, there was an associated non-significant increase in incidence of health issues; in areas where industrial activity did not change, there was an associated non-significant, small decrease in incidence of health issues; and, in areas where industrial activity decreased, there was an associated significant decrease in incidence of health issues.

6. Produced Water Treatment Technologies

6.1 Technologies at Current Subpart E Sites in Wyoming

In Wyoming, the typical treatment used at Subpart E sites starts with separating the oil and gas from the produced water. This is typically done using a heater treater (see Figure 4 courtesy of WATTCO), which is a vessel that uses heat to decrease the viscosity of the oil and help emulsions separate. Gases and vapors rise to the top and water accumulates at the bottom. Water is removed using a drain and then flows for additional processing. Some sites also use gun barrel separators. After separation, produced water in Wyoming is typically sent to ponds and/or tanks where additional oil removal is provided via gravity separation and skimming (see Figure 5 for a photograph of a typical skim pond). Emulsion breaking chemicals are typically used to help aid the oil/water separation, and additional chemicals such as biocides and corrosion inhibitors can be used at various locations as well. In some cases, additional treatment for sulfides control is accomplished via aeration, causing precipitates to form (see Figure 6 for a photograph of a newly constructed sulfides treatment basin in Wyoming). After the skim ponds/tanks (or after sulfides treatment, if present) produced water is typically discharged to the receiving water (see Figure 7 for a photograph of a typical outfall in Wyoming). Additional treatment beyond these technologies is generally not occurring in Wyoming. The EPA is aware of one company, however, that is constructing a reverse osmosis treatment facility to provide additional treatment for produced water prior to discharge to meet permit limits for chlorides.

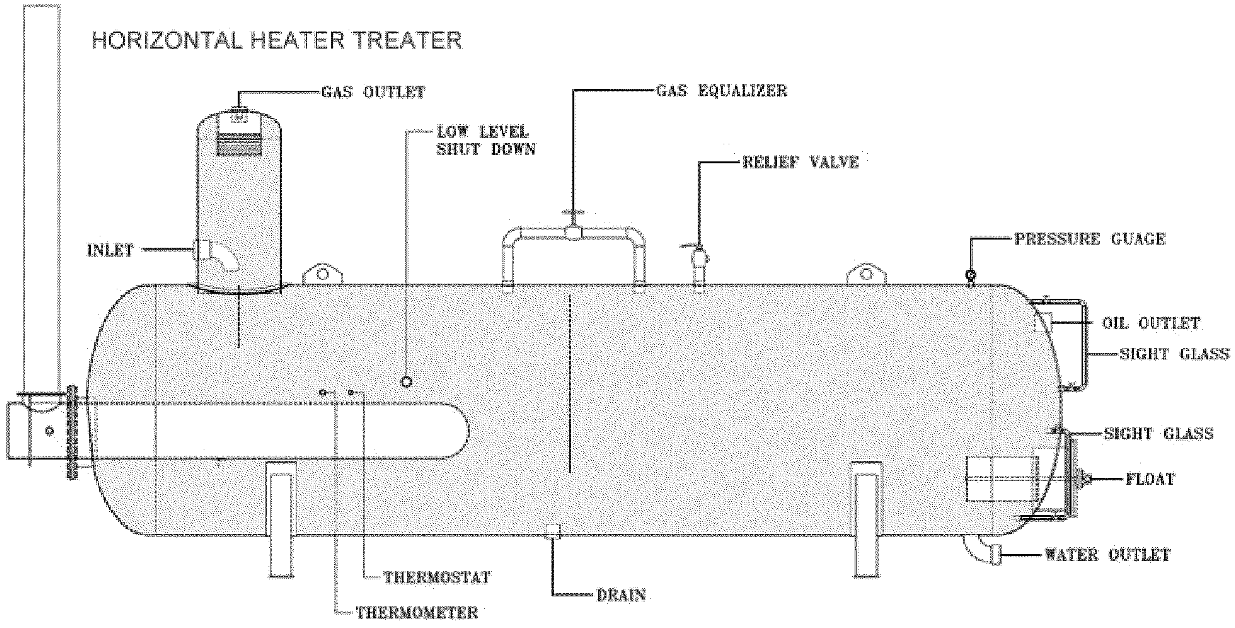

Figure 4. Schematic of a Typical Heater Treater

Figure 5. Typical Skim Pond with Bird Netting at a Wyoming Production Site

Figure 6. Sulfides Treatment Basin at a Wyoming Production Site

Figure 7. Typical NPDES Subpart E Outfall in Wyoming

6.2 Pilot Treatment Systems

According to stakeholders, there is much interest in discharging produced water in other western states, particularly in Texas and New Mexico. This is driven by factors such as increased production (and associated increases in produced water generation), declining injection disposal capacity in some formations, and water scarcity. There are several state consortia that have been formed in recent years that are investigating topics such as produced water characteristics, cost and performance of treatment technologies, and uses of produced water outside of the oil field such as irrigation, rangeland restoration, industrial uses, and augmentation of existing water supplies. The produced water characteristics in areas that are investigating discharge under Subpart E, such as the Permian Basin of Texas and New Mexico, are very different than the characteristics of existing dischargers in Wyoming. In particular, concentrations of TDS and chlorides in Permian Basin produced water are orders of magnitude higher than found in existing discharges in Wyoming. See Figure 8 (Xu et al, 2022) for select data from one study of produced water characteristics in the Permian Basin[14]. The mean TDS concentration of 46 produced water samples from five locations in the Permian Basin was 128,423 mg/L.

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[14] Total radium was calculated by the EPA as the sum of radium-226 and radium-228.

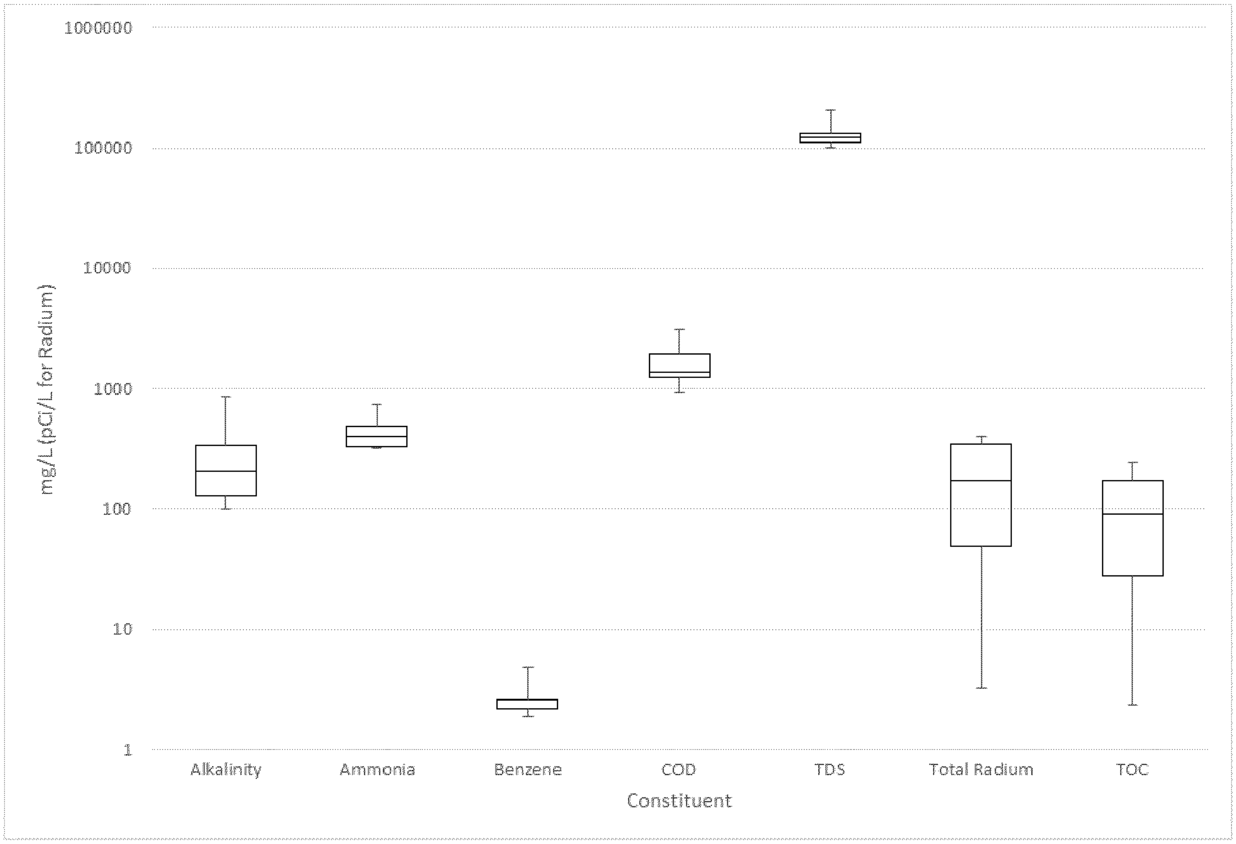

Figure 8. Permian Basin Produced Water Characterization Data (Xu 2022)

As a result, produced water in these and other areas will likely require desalination to be of "good enough quality" for use in agriculture or wildlife propagation, as well as other proposed beneficial uses in the future, and to comply with water quality standards. Technologies under investigation include thermal desalination and membrane-based processes. Permian produced water generally will also require varying levels of pretreatment to protect the desalination step, particularly for membrane processes. In addition, toxic compounds such as soluble organics and ammonia that can carry through the desalination step will generally require polishing to protect aquatic resources. Recognizing that there is work to be done in this area, entities have invested in work to develop and test treatment trains to economically treat produced water. For example, several companies, in concert with the New Mexico Produced Water Research Consortium, have been testing various technologies to treat produced water (see Delanka-Pedige et al, 2024, Tarazona et al, 2024a, Tarazona et al 2024b, Van Houghton et al, 2024a, and Van Houghton et al 2024b). The EPA toured two of the pilot projects during the study. The first site that the EPA toured was operated by NGL Water Solutions. The pilot treatment plant uses a multi-step treatment train incorporating proprietary technologies, including biological treatment, membrane filtration and ion exchange, to treat Permian Basin produced water. The second site that the EPA toured was operated by Texas Pacific Water Resources. This pilot also uses a multi-step treatment train. Figure 9 shows the various stages in the Texas Pacific pilot treatment process as well as the constituent categories that are targeted for removal in the various unit processes. Figure 10 shows a schematic of the pilot treatment train.

Stage	Treatment process	Targeted constituents
1	Oxidation and physical separation	Solids and oil
2	Coagulation and filtration	Suspended solids, hydrocarbons, and iron
3	Freeze desalination	Dissolved solids
4	Filtration through anionic charged glass sand media filter and activated carbon filter	Dissolved solids, Inorganic compounds, volatile organic compounds, microbial contaminants
5	Reverse Osmosis	Dissolved solids and organics
6	GAC + Disinfection via UV Light	Residual organic and inorganic compounds and micro-organisms

Figure 9. Texas Pacific Water Resources Pilot Treatment Train

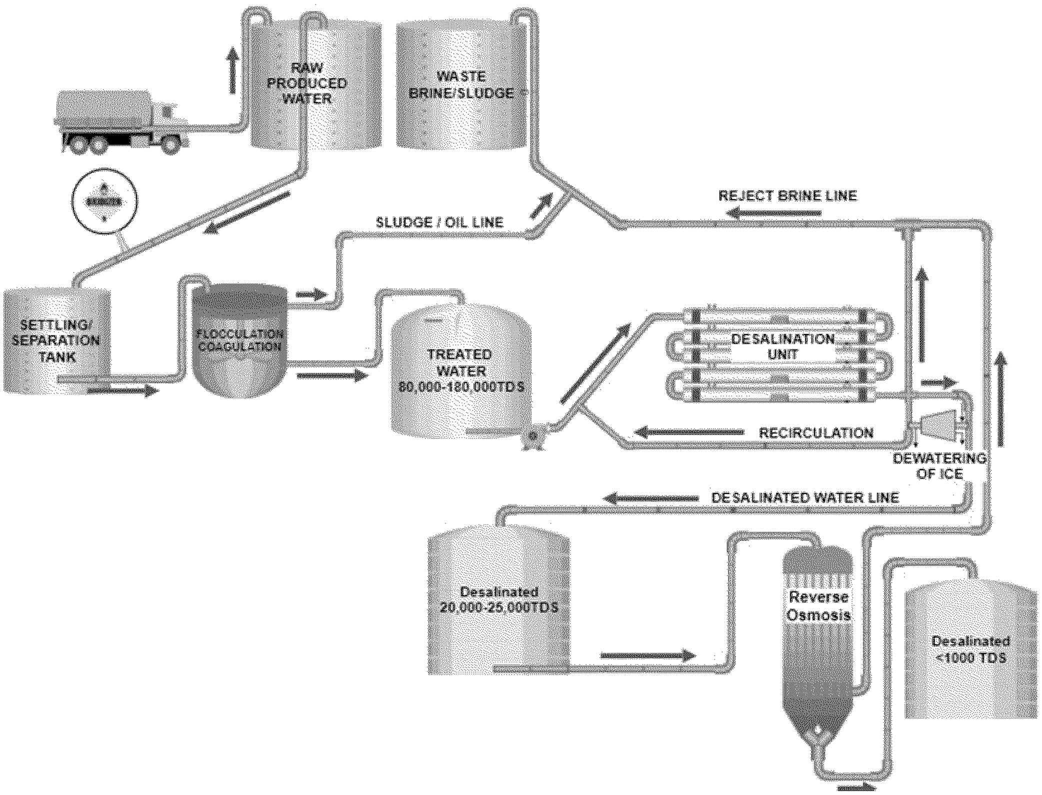

Figure 10. Texas Pacific Water Resources Pilot Treatment Schematic

In addition to the two pilot projects that the EPA toured, the Agency met with several vendors during the study to discuss planned, in-process, or completed pilot projects. These include Bechtel, Circle Verde, Badwater Alchemy, and Devon Energy. The EPA expects that additional information and data from these and other pilot projects will be available and in the public domain throughout calendar year 2025 and will help inform any future Agency efforts.

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Texas Permian Future Generations

Public Comments on Land Application of Produced Water;
RPN 2026-006-309-OW

EXHIBIT 8

From: Caroline Crow
To: "Shannon Gibson"
Cc: Ryan Rakowitz; Gwen Ricco; WQDPIR; Rules; CHIEFCLK
Subject: RE: Request for Extension of Comment Period: Rule Project No. 2026-006-309-OW
Date: Wednesday, June 10, 2026 1:53:00 PM
Attachments: image002.png

Hi Ms. Gibson,

Thank you very much for your email. I appreciate it.

We do believe that there is a particular reason for the Executive Director to extend the public comment period. There is significant public interest in this rulemaking—25 public comments have already been filed.

At the same time, however, there is very limited information supporting the substantive rules out for comment that allow treated produced water's land application near drinking water and other water resources. Our public information request is directly related to the rulemaking and seeking information TCEQ relied on to establish the distance limitations related to the land application of treated produced water. Specifically, our request seeks the technical information TCEQ is relying on to support the substance of the proposed rules. For example, the rulemaking includes a 100-foot distance limitation from waters of the state, and we specifically requested: "Support, science, technical reports, or memoranda justifying the 100 ft buffer from water sources in Rule Project No. 2026-006-309-OW." This is relevant information the public needs to understand what TCEQ is relying on for that distance. We have requested this information twice, and it has not been received. We have paid for the relevant information, but it will not be released until 10 days after this comment period has closed.

Further, we don't believe that an extension of the public comment period requires the Executive Director to deviate "from the manner in which she is required to conduct this Rulemaking" for several reasons. First, the rulemaking is being adopted pursuant to legislation (SB 1145), and that legislation did not include a timeline for corresponding rule adoption. This extension would not violate any legislative requirements associated with this rulemaking. Second, from past practice, it appears that the Executive Director has discretion over the comment period. For example, there are times TCEQ has chosen to hold an informal comment period before a formal comment period. Additionally, on TCEQ's website, it encourages the public to seek extensions—while couched in weather events—it is clear that there can be other extenuating circumstances, which necessitate comment period extensions. In this case, there is publicly available information responsive to the rulemaking, but it will not be provided until after the comment period has closed. Accordingly, no member of the public can review technical bases and other information they are due to make substantive comments on the proposed rules.
Finally, "it is the policy of this state that each person is entitled, unless otherwise expressly provided by law, at all times to complete information about the affairs of government and the official acts of public officials and employees." Tex. Govt. Code Section 552.001(a). The public needs complete information related to this rulemaking.

As we all know, there is a presumption based on Texas Government Code Section 552.021 which makes virtually all information in the custody of a governmental body available to the public." (Texas Public Information Act Handbook 2026 at 44). We've now been told that there is relevant public information available, but we won't have access to it until after its particular relevance may have expired and the rulemaking comment period will have closed.

We are requesting that TCEQ extend the public comment period for up to 30 days after the public information is received.
We appreciate your time and consideration. Thank you.

Caroline Crow (she/her/hers)
Senior Attorney

EARTHJUSTICE

Because the earth needs a good lawyer

From: Shannon Gibson <Shannon.Gibson@tceq.texas.gov>
Sent: Tuesday, June 9, 2026 2:52 PM
To: Caroline Crow <ccrow@earthjustice.org>
Cc: Ryan Rakowitz <Ryan.Rakowitz@tceq.texas.gov>; Gwen Ricco <Gwen.Ricco@tceq.texas.gov>; WQDPIR <wqdpir@tceq.texas.gov>; Rules <rules@tceq.texas.gov>; CHIEFCLK <chiefclk@tceq.texas.gov>
Subject: RE: Request for Extension of Comment Period: Rule Project No. 2026-006-309-OW

External Sender

Dear Ms. Crow,

Thank you for your email dated June 3, 2026, which requests an extension of the public comment period on Rule Project No. 2026-006-309-OW (Rulemaking) until July 17, 2026. At this time, TCEQ's Executive Director is declining to extend the public comment period.

This Rulemaking is subject to the Administrative Procedures Act, which requires TCEQ to give all interested persons a reasonable opportunity to submit data, views, or arguments, orally or in writing. This Rulemaking provides interested persons with the opportunity to submit public comments during the specified comment period and the scheduled public meeting. Further, this Rulemaking must be "conducted in the manner the commission deems most suitable to obtain all relevant information and testimony on proposed rules as conveniently, inexpensively, and expeditiously as possible without prejudicing the rights of any person." After the end of the public comment period, the Executive Director will respond to all timely comments in her Response to Comments, which will be among the required documents the Executive Director will submit to the Commission for final action. (*See* 30 Tex. Admin. Code Ch. 20; *see also* Tex. Gov't Code, Ch 2001.)

Your request to extend the public comment period alludes to the likelihood of not receiving certain documents that were requested in a public information request (PIR), particularly Pilot Program files from the Railroad Commission of Texas (RRC) that you state "informed Rule Project No. 2026-006-309-OW." However, the documents TCEQ received related to the RRC Pilot Program did not inform TCEQ's rulemaking. Therefore, the Executive Director does not believe the anticipated date of receiving the documents requested in your PIR will have any substantive impact or hinder your opportunity to submit public comments on this Rulemaking prior to the close of the comment period. (*See* 30 Tex. Admin. Code Ch. 20 and Ch. 55; *see also* Tex. Gov't. Code, Ch. 2001.)

Unless there is a particular reason that the Executive Director should deviate from the manner in which she is required to conduct this Rulemaking, such as the proposed extension of the public comment period, this Rulemaking must proceed as specified in the public notices and in accordance with the applicable requirements relating to agency rulemaking.

Please feel free to reach back out if you have additional questions about this Rulemaking.

Best Regards,
Shannon Gibson
Special Assistant
Water Quality Division

Take Care of Texas
TakeCareOfTexas.org

How is our customer service? Fill out our online customer satisfaction survey at www.tceq.texas.gov/customersurvey

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From: Caroline Crow <ccrow@earthjustice.org>
Sent: Wednesday, June 3, 2026 10:44 AM
To: WQDPIR <wqdpir@tceq.texas.gov>; Rules <rules@tceq.texas.gov>; CHIEFCLK <chiefclk@tceq.texas.gov>
Cc: Ryan Rakowitz <Ryan.Rakowitz@tceq.texas.gov>; Gwen Ricco <Gwen.Ricco@tceq.texas.gov>; Shannon Gibson <Shannon.Gibson@tceq.texas.gov>
Subject: Request for Extension of Comment Period: Rule Project No. 2026-006-309-OW
Importance: High

Good morning y'all,

In April, I submitted two different public information requests seeking information relevant to the current open comment period on Rule Project No. 2026-006-309-OW. The first request returned no information responsive to my request, and no information responsive to the second request will be received until after the close of the comment period. Accordingly, I am writing to request that the Commission extend this comment period until information can be provided by the TCEQ and reviewed by the public: through and until July 17, 2026.

Further, information to support this rulemaking (beyond the Commission's Executive Summary) appears to be public, but it is not readily available through searches on the Commission's' website. The first PIR I submitted requesting records relating to this rulemaking was dated April 24, 2026 (PIR No. 114850). In response to that first request, I only received a copy of the Executive Summary and the proposed rule amendments in return—and nothing else.

In PIR No. 114850 dated April 24, 2026, I requested the following, but I only received a copy of the Executive Summary and proposed rule amendments.

1. Texas Railroad Commission files and permitting data that informed Rule Project No. 2026-006-309-OW;
2. Communications between RRC and TCEQ related to Rule Project No. 2026-006-309-OW;
3. Communications or memoranda between RRC and TCEQ related to jurisdiction; and
4. Technical support, data, records, reports, or studies supporting Rule Project No. 2026-006-309-OW and specifically supporting the portion of the rule requiring a wastewater treatment plant unit or land where irrigation using wastewater effluent occurs, be located a minimum horizontal distance of 100 feet from a water in the state.

On April 30, 2026, I submitted PIR No. 115043, requesting the following:

1. Communications and/or memoranda between the Texas Railroad Commission and the Texas Commission on Environmental Quality related to jurisdiction and amending the Memorandum of Understanding between the two agencies codified at 30 Texas Administrative Code Section 7.117;
2. Communications and/or memoranda between the Texas Railroad Commission and the Texas Commission on Environmental Quality related to implementing SB 1145 and amending Texas Water Code Section 26.131 and transferring permit authority from the Railroad Commission to the Texas Commission on Environmental Quality;
3. Support, science, technical reports, or memoranda justifying the 100 ft buffer from water sources in Rule Project No. 2026-006-309-OW.
4. Copies of the Railroad Commission permitting pilot files referencing during the Water Quality Advisory Working Group meeting on April 14, 2026;
5. Texas Commission on Environmental Quality materials supporting implementation of SB 1145 including communications, memoranda, reports, and other documents.

Just today—with only limited time left in the comment period—I received the below email that I will not receive relevant records to my April 30th (PIR No. 115403) until June 26, 2026, which is after this rulemaking comment period has closed.

Is there a procedure to request an extension of time to comment on the rules based on the lack of readily available (but public information) related to this rulemaking and the delay in processing these public information requests related to the proposed rules?

I'm happy to file a formal comment requesting an extension, if necessary. Please advise. We appreciate all y'all do. Thank you in advance!

Caroline Crow (she/her/hers)
Senior Attorney

EARTHJUSTICE

Because the earth needs a good lawyer

From: WQDPIR <wqdpir@tceq.texas.gov>
Sent: Wednesday, June 3, 2026 8:45 AM
To: Caroline Crow <ccrow@earthjustice.org>
Subject: PIR 115043 Deposit Payment Received

External Sender

Caroline Crow,

Good morning, this email is to inform you that TCEQ has received your deposit payment, and we anticipate that all files will be ready for release by June 26, 2026.

Shall you have any questions, please do not hesitate to let us know by replying to the email or by contacting us at wqdpir@tceq.texas.gov; please reference your PIR number for easier tracking in your reply.

Thank you,
Michelle Hill

PIR Coordinator
Texas Commission on Environmental Quality (TCEQ)
Water Quality Division, MC 148
P.O. Box 13087

Austin, Texas 78711-3087

How is our customer service? Fill out our online customer satisfaction survey at www.tceq.texas.gov/customersurvey