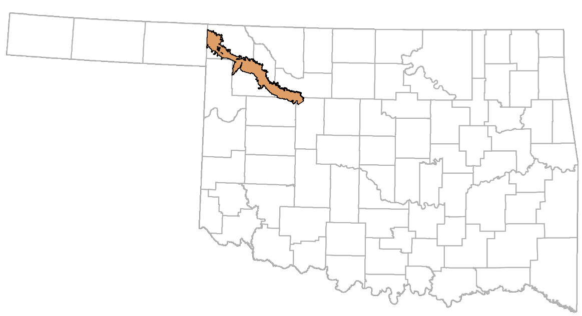
**40-YEAR UPDATE**

MAXIMUM ANNUAL YIELD DETERMINATION

FOR THE

BEAVER-NORTH CANADIAN RIVER ALLUVIUM AND TERRACE
GROUNDWATER BASIN, REACH I

Executive Summary Report



Oklahoma Water Resources Board
Water Rights Administration Division
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## Introduction

Title 82, Section 1020.4 of the Oklahoma statutes requires the Oklahoma Water Resources Board [OWRB] to conduct hydrologic investigations of major and minor groundwater basins or subbasins prior to the establishment of a tentative maximum annual yield and that at least every twenty (20) years after issuance of the final order determining the maximum annual yield, the Board shall review and update, if necessary, the hydrologic investigations.

A "groundwater basin" is defined in the Oklahoma Administrative Code Title 785, Section 30-1-2 as a distinct underground body of water overlain by contiguous land and having substantially the same geological and hydrological characteristics and yield capabilities from which groundwater wells in a "major groundwater basin" yield a least fifty (50) gallons per minute on the average basin wide, if from a bedrock aquifer and at least one hundred fifty (150) gallons per minute on the average basin wide if from an alluvium and terrace aquifer [§82:1020.1(3)]. The tentative determination of the maximum annual yield must be based on the following:

1. The total land area overlying the basin or subbasin;
2. The amount of water in storage in the basin or subbasin;
3. The rate of recharge to and total discharge from the basin or subbasin;
4. Transmissivity of the basin or subbasin; and
5. The possibility of pollution of the basin or subbasin from natural sources.

The statute further provides that the maximum annual yield of each groundwater basin or subbasin shall be based upon a minimum basin or subbasin life of twenty (20) years from the effective date of the order establishing the final determination of the maximum annual yield [§82:1020.5].

On August 9, 1983, a final order for Reach I of the Beaver-North Canadian River Alluvium and Terrace Groundwater Basin was signed by the chairman of the board, establishing an equal proportionate share of one acre-foot per acre per year. The final order determinations were based on information provided in the U.S. Geological Survey [USGS] Open-File Report 81-783 entitled Geohydrology and Numerical Simulation of the Alluvium and Terrace Aquifer along the Beaver-North Canadian River from the Panhandle to Canton Lake, Northwestern Oklahoma (Davis and Christenson, 1981).

The purpose of this report is to summarize hydrologic data from an updated hydrologic investigation necessary to update the maximum annual yield of the Beaver-North Canadian River Alluvium and Terrace Groundwater Basin in accordance with Oklahoma groundwater law. Data was summarized from the USGS Scientific Investigation Report 2015-5183 entitled Hydrogeological Framework, Numerical Simulation of Groundwater Flow, and Effects of Projected Water Use and Drought for the Beaver-North Canadian River Alluvial Aquifer, Northwestern Oklahoma (Ryter and Correll, 2015).

## Study Area

The Beaver-North Canadian River [BNCR] Alluvium and Terrace Groundwater Basin (Reach I) underlies approximately 545,863 acres (853 square miles [$mi^2$]) of land along approximately 162 miles of the Beaver and North Canadian Rivers in northwestern Oklahoma, extending from the Beaver-Harper County line to Canton Lake in northwestern Blaine County.

## Summary of Hydrogeologic Characteristics

- The Beaver-North Canadian River Alluvium and Terrace Groundwater Basin is composed of Quaternary- and Tertiary-age sediments (sand, silt, clay, and gravel) that uncomformably overlie Permian-age bedrock units principally composed of shale and sandstone. The semi-consolidated Tertiary-age sediments are associated with the Ogallala Formation in Harper County.

- The saturated thickness of the groundwater basin can vary from less than a foot to a maximum of about 230 feet where Ogallala Formation sediments are present but is typically less than 100 feet where the Ogallala Formation sediments are absent. The average saturated thickness of Reach I as determined at the end of the 1980–2011 transient model period was about 35 feet (including cells with a saturated thickness of zero [dry cells]). The aquifer base and potentiometric surface were reevaluated, resulting in a mean saturated thickness of 30 feet (including dry cells).

- Six (6) published aquifer tests from Woodward County showed a transmissivity range of 2,144 to 8,710 square feet per day ($ft^2$/day), with a mean of 5,315 $ft^2$/day (Woods and Stacy, 1965). Davis and Christenson (1981) indicated a model transmissivity range of 0 to 8,030 $ft^2$/day with a mean of 1,780 $ft^2$/day.[1] Model-calibrated horizontal hydraulic conductivity (Kh) for Reach I ranged from 6 to 279 feet per day (ft/day), with a mean of 70 ft/day.

- The specific yield (Sy) determined from three (3) published aquifer tests ranges from 0.1 to 0.24, with a mean of 0.16 (Fox and Kizer, 2009; Mogg and others, 1960). Model-calibrated specific yield (Sy) ranged from 0.11 to 0.29, with a mean of 0.19.[2] This Sy value is larger than the mean values determined for other alluvium and terrace aquifers in western Oklahoma, which range between 0.1 and 0.16.

- The mean annual recharge estimated from a transient soil-water balance model (Westenbroek and others, 2010) was 136,400 acre-ft/year in Reach I (3.01 inches per year [in/year]) for the period 1980–2011; annual recharge arrays derived from this transient model were used as inputs for the numerical flow model. Reach I model calibrations resulted in a slightly higher mean annual recharge estimate of 143,990 acre-ft/year (3.15 in/year) for the same period; when adjusted to the updated OWRB defined basin area (see *Chnges in Basin Area* subsection), the mean annual recharge was adjusted to 143,136 acre-ft/year.

- The total amount of available groundwater in storage estimated from the USGS model files was about 3.5 million acre-feet (sum of model cell storage values calculated from the multiplication of cell area, cell saturated thickness, and cell specific yield). The available water in storage was adjusted to about 3.1 million acre-feet following a reanalysis of the aquifer base and potentiometric surface. The storage volumes determined from the 2016 USGS model files and OWRB reanalysis are smaller than the 4.1 million acre-feet estimated in the 1981 hydrologic investigation because of the larger (0.29) specific yield estimate used for that model. The OWRB volume is less than the USGS volume because of the reduced saturated thicknesses in Harper, Woodward, and Major counties.

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1. The range is reflective of transmissivity values from the modeled no-flow boundary surrounding the basin (T = 0) to the values determined from the multiplication of hydraulic conductivity (Plate 7) and saturated thickness (Plate 8).

2. Initial estimates of Sy adjusted during the numerical-model calibration were determined from a logarithmic regression relationship between Kh and Sy based on published values for different geologic materials following the method of Mashburn and others (2013). The initial mean value of Sy for Reach I was 0.16. Likewise, the initial estimates of Kh were taken from ranges published by Fetter (1994).

## Maximum Annual Yield and Equal Proportionate Share Determination

The definition of the Life of a groundwater basin or subbasin indicates that there are two endpoints for the determination of the maximum annual yield, either fifty percent of the basin area will retain a saturated thickness allowing for pumping of the maximum annual yield for a minimum twenty-year life of basin OR the average saturated thickness of the basin will be calculated to be maintained at five feet for alluvium and terrace aquifers and fifteen feet for bedrock aquifers, respectively. For simplicity, these scenarios are herein referred to as the fifty percent and full depletion scenarios. In nearly all cases, both endpoints will not be satisfied at the same time because of the non-uniform geometry of groundwater basins. This gives the Board flexibility to determine how to manage each groundwater basin.

- Maximum annual yield (MAY): *"a determination by the Board of the total amount of fresh groundwater that can be produced from each basin or subbasin allowing a minimum twenty (20) year life of basin or subbasin"*

- Equal proportionate share (EPS): *"the maximum annual yield of water from a groundwater basin or subbasin which shall be allocated to each acre of land overlying such basin or subbasin. It shall be that percentage of the maximum annual yield, determined as provided by 82 O.S., §1020.5 and 785:30-9-2 which is equal to the percentage of the land overlying the fresh groundwater basin or subbasin which is owned or leased by an applicant for a regular permit"*.

In pursuance of the fifty percent scenario, the United States Geological Survey (USGS) developed a finite-difference numerical groundwater-flow model for Reach I of the Beaver-North Canadian River Groundwater Basin based on available hydrogeologic data which included historical data from previous investigations and data queried from the OWRB well driller's database, the USGS National Water Information System, and the Oklahoma Climatological Survey. To determine the EPS rate for Reach I, one hypothetical groundwater-pumping well was put in each active model cell and pumped at the same applied rate over several iterations until half of the model cells had a saturated thickness of five feet or less. The EPS rates listed in **Table 1** represent the applied rates used in the numerical flow model to achieve the forecasting goal; The applied rate refers to the uniform rate set for each pumping cell within the model domain. The MAY is calculated as the cumulative amount of water recovered (pumped) over a simulation period divided by the length of the simulation period. The MAY volumes for each life of basin period and recharge scenario are listed in **Table 1.**

**Table 1**. Equal-proportionate-share rates for select life of basin periods in Reach I of the Beaver-North Canadian River Alluvium and Terrace Groundwater Basin, northwestern Oklahoma (Ryter and Correll, 2015).

| Period (years) | Reach I applied EPS pumping rates | | |
|---|---|---|---|
| | Recharge reduced by 10 percent | No change in recharge | Recharge increased by 10 percent |
| 20 | 0.53 | 0.57 | 0.60 |
| 40 | 0.49 | 0.54 | 0.58 |
| 50 | 0.48 | 0.53 | 0.57 |
| | Reach I MAY volumes (from model) | | |
| 20 | 210,524.88 | 225,458.75 | 240,102.24 |
| 40 | 216,795.62 | 203,953.71 | 184,379.68 |
| 50 | 176,629.04 | 193,215.24 | 209,186.14 |

The aquifer base, potentiometric surface, and basin area were reanalyzed to address conflicts between the published data and well log data from the OWRB well drillers database, particularly in Harper County where the Ogallala is present. Adjustments to the base, potentiometric surface, and basin area changed the aquifer saturated thickness and the volume of water in storage. These changes necessitated new model simulations. The EPS rates and MAY volumes listed in the upper half of **Table 2** represent values for Reach I of the basin as determined from the updated OWRB analytical model (calibrated to the USGS model) to achieve the fifty percent scenario. The EPS rates and MAY volumes listed in the lower half of **Table 2** reflect the removal of prior rights, including existing regular permits.

**Table 2**. Equal-proportionate-share rates for select life of basin periods in Reach I of the Beaver-North Canadian River Alluvium and Terrace Groundwater Basin as determined from the updated OWRB analytical Excel pumping model, for the fifty percent basin depletion scenario.

| Period (years) | Reach I EPS pumping rates (Final applied rate) | | |
|---|---|---|---|
| | Recharge reduced by 10 percent | No change in recharge | Recharge increased by 10 percent |
| 20 | 0.56 | 0.60 | 0.64 |
| 40 | 0.53 | 0.57 | 0.60 |
| 50 | 0.53 | 0.57 | 0.60 |
| | **Reach I MAY volumes (from model)** | | |
| 20 | 216,262.28 | 228,939.63 | 241,616.98 |
| 40 | 194,073.48 | 205,760.15 | 217,446.81 |
| 50 | 186,600.50 | 197,861.12 | 209,121.73 |
| | | | |
| | **Reach I EPS pumping rates (After removal of prior rights)** | | |
| 20 | 0.44 | 0.48 | 0.52 |
| 40 | 0.40 | 0.44 | 0.48 |
| 50 | 0.40 | 0.44 | 0.48 |
| | **Reach I MAY volumes (After removal of prior rights)** | | |
| 20 | 121,920.58 | 134,597.93 | 147,275.28 |
| 40 | 99,731.78 | 111,418.45 | 123,105.11 |
| 50 | 92,258.80 | 103,519.42 | 114,780.03 |

An EPS rate of 0.60 (acre-feet/acre)/year and a MAY volume[3] of 228,939.63 acre-feet/year were estimated from the OWRB analytical model for the 20-year basin life. To accommodate the 147 prior rights and ensure they are adequately protected, 33,817 acre-feet of water rights established before July 1, 1973, in Reach I, were removed from the model-derived MAY. Removal of the prior rights reduced the MAY to about 195,123 acre-feet/year. As of the date of this report, there are 194 active regular groundwater-use permits within Reach I. Collectively, these permits constitute a total annual allocation of 60,524.7 acre-feet. Because regular permits retain their allocation amounts, they also had to be subtracted from the model-derived MAY, which reduced the MAY to 134,597.9 acre-feet/year. The final EPS rate for the undeveloped lands was determined to be 0.48 (acre-feet/acre)/year for the fifty percent scenario over a 20-year basin life. Existing dedicated lands will retain an EPS rate of 1.0 (acre-feet/acre)/year per the 1983 final order. To note, the full depletion scenario was not statutorily permitted until 1994. The relatively large difference between the final order EPS rate and the rates determined by the USGS model by Ryter and Correll (2016) and the OWRB analytical model speaks to the sensitivity of each model to parameterization. The Davis and Christenson (1981) numerical flow model yielded a 20-year EPS rate of 0.73 (acre-feet/acre)/year, which was increased to 1.0 (acre-feet/acre)/year through the addition of twenty percent return flow. The USGS

3. Unlike numerical flow models, where the final EPS and MAY values are determined by mass balancing during a simulation, analytical calculators require the user to set predefined volumes at which the model will stabilize based on estimated water remaining in storage.

and OWRB models did not include return flows — instead, any water pumped during each timestep was removed from the model domain. Return flow does occur, but under the extreme pumping conditions set in the EPS scenarios, the maximum available water capacity of the soil would be quickly reached, so any additional pumped water would flow out of each model cell as runoff.

The updated OWRB analytical model was also used to determine the EPS rates and MAY volumes for the full depletion scenario, the values of which are listed in **Table 3**. The USGS numerical flow model did not simulate this MAY determination endpoint.

**Table 3**. Equal-proportionate-share rates for select life of basin periods in Reach I of the Beaver-North Canadian River Alluvium and Terrace Groundwater Basin were determined from the updated OWRB analytical Excel pumping model, for the full depletion endpoint.

| Period (years) | Reach I EPS pumping rates (Final applied rate) | | |
|---|---|---|---|
| | Recharge reduced by 10 percent | No change in recharge | Recharge increased by 10 percent |
| 20 | 1.19 | 1.24 | 1.30 |
| 40 | 0.93 | 0.98 | 1.02 |
| 50 | 0.93 | 0.98 | 1.02 |
| | Reach I MAY volumes (from model) | | |
| 20 | 278,554.22 | 288,888.35 | 299,222.47 |
| 40 | 206,676.71 | 214,992.17 | 223,307.63 |
| 50 | 197,113.65 | 204,857.22 | 212,600.80 |
| | | | |
| | Reach I EPS pumping rates (After removal of prior rights) | | |
| 20 | 1.14 | 1.20 | 1.26 |
| 40 | 0.86 | 0.90 | 0.95 |
| 50 | 0.86 | 0.90 | 0.95 |
| | Reach I MAY volumes (After removal of prior rights) | | |
| 20 | 184,212.52 | 194,546.65 | 204,880.77 |
| 40 | 112,335.01 | 120,650.47 | 128,965.93 |
| 50 | 102,771.95 | 110,515.52 | 118,259.10 |

An EPS rate of 1.24 (acre-feet/acre)/year and a MAY volume of 288,888.35 acre-feet/year were estimated from the OWRB analytical model for the 20-year basin life. To accommodate the 147 prior rights and 194 active regular groundwater-use permits in Reach I and ensure they are adequately protected, 94,341.7 acre-feet of water rights were removed from the model-derived MAY, reducing the volume to 194,546.7 acre-ft/year. The final EPS rate for the undeveloped lands was determined to be 1.20 (acre-feet/acre)/year based on the model-derived MAY and existing dedicated lands permitted at 1.0 (acre-feet/acre)/year. However, because the final EPS rate exceeds the 1983 final-order EPS rate, all existing dedicated lands would be eligible for a rate increase equivalent to the difference between the existing rate and rate derived by dividing the nominal MAY by the full basin area; the final EPS for the entire basin would be 1.12 (acre-feet/acre)/year after the removal of prior rights. The full depletion scenario is a much more extreme pumping scenario than the one used to determine the 1983 final order rate; any similarity between the rates is coincidental.

For completeness, EPS pumping rates and MAY volumes were also estimated using the original version of the OWRB analytical calculator developed by technical staff in the early 2000s. This analytical calculator was used to determine the tentative and final EPS rate for Vamoosa-Ada, Ogallala-Northwest, Ashland Isolated Terrace, Cherokee Group, El Reno, Woodbine, Little River, Haworth Isolated Terrace regions 1&2, Pennsylvanian, Cache Creek, Post Oak, Hennessey-Garber, Beaver Creek, North-Central Oklahoma, and

Antlers aquifers. In each case, the EPS pumping rates were determined based on an amalgamation of the two Life of Basin endpoints, where pumping linearly declines from 100% of the basin at interval one to 50% of the basin at interval 10, and where the volume remaining in storage is equal to the basin area multiplied by the mean specific yield and averaged saved saturated thickness of five (5) or fifteen (15) feet depending on whether it was an alluvial or bedrock aquifer.

**Table 4**. Equal-proportionate-share rates for select life of basin periods in Reach I of the Beaver-North Canadian River Alluvium and Terrace Groundwater Basin were determined from the original OWRB analytical Excel pumping model, for the full depletion endpoint.

| Period (years) | Reach I EPS pumping rates (Final applied rate) | | |
|---|---|---|---|
| | **Recharge reduced by 10 percent** | **No change in recharge** | **Recharge increased by 10 percent** |
| 20 | 0.65 | 0.69 | 0.72 |
| 40 | 0.49 | 0.52 | 0.56 |
| 50 | 0.45 | 0.49 | 0.53 |
| | **Reach I MAY volumes (from model)** | | |
| 20 | 258,821.09 | 273,134.69 | 287,448.29 |
| 40 | 193,821.74 | 208,135.34 | 222,448.94 |
| 50 | 180,821.87 | 195,135.47 | 209,449.07 |
| | | | |
| | **Reach I EPS pumping rates (After removal of prior rights)** | | |
| 20 | 0.54 | 0.58 | 0.62 |
| 40 | 0.35 | 0.39 | 0.43 |
| 50 | 0.32 | 0.36 | 0.40 |
| | **Reach I MAY volumes (After removal of prior rights)** | | |
| 20 | 164,479.39 | 178,792.99 | 193,106.59 |
| 40 | 99,480.04 | 113,793.64 | 128,107.24 |
| 50 | 86,480.17 | 100,793.77 | 115,107.37 |

An EPS rate of 0.69 (acre-feet/acre)/year and a MAY volume of 273,134.69 acre-feet/year were estimated from the OWRB analytical model for the 20-year basin life. To accommodate the prior rights and active regular groundwater-use permits, 94,341.70 acre-feet was removed from the model-derived MAY, reducing the volume to 178,792.99 acre-feet/year. The final EPS rate for the undeveloped lands was determined to be 0.58 (acre-feet/acre)/year, with existing dedicated lands permitted at 1.0 (acre-feet/acre)/year.

## Changes in Groundwater Basin Area

The 1983 final order for the Beaver-North Canadian River Alluvium and Terrace Groundwater Basin (Reach I) established a groundwater basin area of about 426,000 acres (666 $mi^2$); the basin area was defined within the final order under Findings of Fact 6 and 7 as the area with a saturated thickness of at least five (5) feet as of July 1, 1973. The groundwater basin area was derived from the result of simulation 5 (**Figure 1**; Plate 13 in Davis and Christenson, 1981), which simulated flow for the period 1957–1973 using a constant recharge rate of one (1) inch per year and annual pumping rates based on reported groundwater use for the three largest water use categories in the study area (irrigation, public supply, and industrial). To note, about 100.7 $mi^2$ (64,448 acres) of the study area[4] were excluded from the model domain purportedly

4. The basin area of Reach I in Davis and Christenson (1981) was estimated to be about 845.7 $mi^2$, of which about 827.6 $mi^2$ are underlain by Quaternary age Alluvium and Terrace deposits. The study area included Canton Lake (11.07 $mi^2$) and Fort Supply Reservoir (2.64 $mi^2$), and several bedrock outcrops (cumulative area of about 4.4 $mi^2$).

because they had no flow (**Figure 2**; yellow areas); the largest of these areas located east of Fort Supply Lake between T.22–24N., R.22WI was excluded from the model domain because "*the band of little or no saturated thickness at the northern edge of this area precludes significant flux from the area to the Beaver-North Canadian River.*" Smaller areas along the basin's edges were also excluded from the model domain because either flow was directed away from the Beaver-North Canadian River or the flow was considered negligible (related to the thinning of aquifer sediments).

In addition to the no-flow areas, about 60.8 $mi^2$ (38,912 acres) of the study area were excluded from the equal proportional share simulation because they had little (less than 5 feet) or no saturation during the 1957 steady-state model calibration (**Figure 2**; blue areas). In total, about 161.5 $mi^2$ (103,360 acres) were excluded from the simulations requested by the Oklahoma Water Resources Board for the determination of the equal proportionate share. At the end of simulation 5, about 16.5 $mi^2$ of additional basin area had a saturated thickness that fell below five (5) feet (**Figure 2**; orange areas), bringing the total area with little to no saturation to about 178 $mi^2$; the subtraction of this area from the study area (845.7 $mi^2$) is how the authors of the 1981 model report came to a basin area of 666 $mi^2$.

The updated hydrologic investigation report by Ryter and Correll (2016) used the same study area as Davis and Christenson (1981), albeit with a more detailed boundary defined using the Woodward hydrologic atlas surface geology map (Morton, 1980). For modeling purposes, the USGS shifted the Reach I to Reach II transition line about 1.9 miles southeast of Lake Canton to avoid boundary condition issues; the shifted transition line increased the model basin to 858 $mi^2$ (549,439 acres). Unlike the Davis and Christenson model, the Ryter and Correll model included areas with little or no saturated thickness because the groundwater level fluctuates throughout a simulation period and because recharge to these areas can flow into the thickener areas or be pumped out.

A revised groundwater basin boundary was defined for Reach I based on updated geologic maps for northwestern Oklahoma published by the Oklahoma Geological Survey for the Buffalo, Woodward, and Fairview quadrangles (Stanley and Suneson, 2002; Stanley, 2002; Stanley and others, 2002) and a technical review by OWRB staff geologists (**Figure 3**); the revised basin boundary adheres to the lateral extent established in the 1983 final order. The groundwater basin area (excluding the areas of Canton and Fort Supply lakes) was determined to be about 853 $mi^2$ (545,863 acres)

## EPS Recommendation

The Water Right Administration Division recommends that an equal proportionate share rate between 0.48 (acre-ft/acre)/year (fifty percent scenario) and 1.12 (acre-ft/acre)/year (full depletion scenario) be adopted for the undeveloped land areas based on the two life of a groundwater basin endpoints; existing regular permits with an EPS rate of 1.0 (acre-ft/acre)/year would need to be increased to 1.12 (acre-ft/acre)/year if that full depletion scenario is adopted. The model-determined maximum annual yield ranged between 228,940 and 288,888 acre-feet per year, or about 4.58 to 5.78 million acre-feet over the next 20 years. Current dedicated lands with an EPS rate of 1.00 (acre-ft/acre)/year correspond to a MAY of 60,524.7 acre-feet/year or about 1.21 million acre-feet over the next 20 years, and current prior rights correspond to a MAY of 33,817.0 acre-feet/year or about 676,340 acre-feet over the next 20 years.

The model-determined MAY volumes assume immediate full basin development and continuous pumpage at the applied EPS rate over a 20-year life of the basin. Neither assumption reflects current or expected future demand from the Beaver-North Canadian River Alluvium and Terrace Groundwater Basin. Of the 94,341.7 acre-feet per year allocated to current active regular and prior rights permits, only about seventeen

(17) percent is used annually based on the mean annual groundwater use of 15,309 acre-feet per year reported in Ryter and Correll (2016) for the period 1967–2011. The mean annual groundwater use is equivalent to an EPS rate of 0.03 (acre-ft/acre)/year when equally distributed across the full basin area or about 0.25 (acre-ft/acre)/year when divided into the dedicated lands. In either case, the conservative EPS recommendation should not negatively impact most future beneficial-use landowners.

The Board can elect to adopt any EPS rate between 0.48–1.12 (acre-ft/acre)/year for the undeveloped lands, with the understanding that as the EPS rate increases, the percentage of the basin that will have a saturated thickness of five (5) feet or more will decrease (under the conditions set in the EPS simulations). If the Board elects to maintain the 1983 final order EPS rate of 1.0 (acre-ft/acre)/year, the equivalent MAY value would be about 266,408 acre-ft/year. A Board subcommittee meeting was held on May 15, 2025, to discuss rate options for the basin; the subcommittee members selected an EPS rate of 0.5 (acre-ft/acre)/year for Reach I to be presented to the full Board in the tentative order. An EPS rate of 0.5 (acre-ft/acre)/year is equivalent to a MAY volume of 234,011 acre-feet/year. Existing regular permits would maintain an EPS rate of 1.0 (acre-ft/acre)/year.

## Percent Developed

According to Title 82, Section 1020.6 of the Oklahoma statutes, the Board may prescribe delayed or gradual implementation of equal proportionate share allocations if the current total allocated amount of groundwater from the aquifer is twenty-five percent (25%) or less of the maximum annual yield. The percentage is herein referred to as the “MAY percent developed”. The MAY percent developed for Reach I was calculated to be 41.2 percent for the fifty (50) percent scenario and 32.7 percent for the full depletion scenario (when prior rights allocations are included), using the model-determined maximum annual yield volumes. If the prior rights allocations are not included, the percent developed was calculated to be 26.4 percent for the fifty (50) percent scenario and 21.0 percent for the full depletion scenario. For completeness, a non-statutory percent developed value can be determined for land overlying a groundwater basin that has been dedicated to active regular groundwater permits, herein referred to as the “developed basin area percentage”. Reach I has a developed basin area percentage of 11.1 percent.

## Groundwater Quality

Davis and Christenson (1981) collected water samples from thirty (30) wells within the basin area to determine the concentration of common chemical constituents, with 15 of the sampled wells also being analyzed for trace constituents; all the sampling was conducted during the summer of 1978. Of the 30 samples collected, two (2) samples were sodium chloride type, two (2) samples were calcium sulfate type, and the rest were calcium bicarbonate type. Chemical water types were determined by the predominant cation and anion, where predominant means that the concentration was greater than fifty (50) percent of the total concentration. Of the 30 samples collected, fifteen (15) had one or more chemical constituents with concentrations greater than or equal to the limits set for public supply use.

Eight (8) samples had concentrations of nitrogen that exceeded 10 milligrams per liter (mg/L), nine (9) samples had total dissolved solid concentrations that exceeded 500 mg/L, one (1) sample had a chloride concentration that exceeded 250 mg/L, two (2) samples had sulfate concentrations that exceeded 250 mg/L, two (2) samples had iron concentrations that exceeded 300 micrograms per liter (ug/L), two (2) sites had manganese concentrations that exceeded 50 ug/L, and one (1) sample had a selenium concentration that exceeded 10 ug/L.

As part of the ongoing groundwater monitoring and assessment program (GMAP), the OWRB collected water samples from nineteen (19) wells across the basin area in 2015. All 19 samples were calcium-bicarbonate type; two (2) samples had sodium concentrations that constituted more than 35 percent of the total cation concentration, and one (1) sample had a sulfate concentration that constituted more than 45 percent of the total anion concentration. Seven (7) samples had concentrations of nitrogen that exceeded 10 milligrams per liter, and three (3) samples had TDS concentrations that exceeded 500 mg/L. Summary statistics for selected chemical constituents are shown in **Tables 5 & 6**. Nitrogen (as nitrate) is considered a water quality concern in Reach I of the Beaver-North Canadian River Alluvium and Terrace Groundwater Basin.

**Table 5.** Summary statistics for groundwater-quality data for 30 samples collected by Davis and Christenson (1981)

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; ºC, degrees Celsius; mg/L, milligrams per liter; ug/L, micrograms per liter]

| Parameter | Detection limit | Mean | Min | Percentile | | | Max | EPA Standard |
|---|---|---|---|---|---|---|---|---|
| | | | | 25 | 50 | 75 | | |
| Specific Cond., µS/cm | -- | 757.3 | 210.0 | 371.3 | 542.5 | 771.5 | 2,400.0 | -- |
| Temperature, ºC | -- | 17.4 | 16.0 | 15.6 | 17.0 | 18.0 | 23.5 | -- |
| pH, standard unit | -- | 7.0 | 6.4 | 6.8 | 7.1 | 7.3 | 7.5 | -- |
| Dissolved Solids, mg/L | -- | 507.7 | 148.0 | 238.5 | 352.5 | 539.0 | 1,690.0 | 500 |
| Calcium, mg/L | -- | 84.0 | 25.0 | 50.6 | 68.0 | 92.3 | 270.0 | -- |
| Magnesium, mg/L | -- | 20.1 | 3.9 | 9.5 | 14.0 | 22.5 | 90.0 | -- |
| Sodium, mg/L | -- | 47.2 | 5.5 | 9.8 | 14.5 | 45.8 | 230.0 | -- |
| Potassium, mg/L | -- | 2.7 | 0.9 | 1.6 | 2.1 | 2.9 | 4.6 | -- |
| Sulfate, mg/L | -- | 94.7 | 4.7 | 15.3 | 45.0 | 67.3 | 750.0 | 250 |
| Chloride, mg/L | -- | 53.3 | 3.9 | 8.7 | 18.0 | 42.0 | 330.0 | 250 |
| Bicarbonate, mg/L | -- | -- | -- | -- | -- | -- | -- | -- |
| Fluoride, mg/L | -- | 0.5 | 0.1 | 0.2 | 0.4 | 0.7 | 1.2 | 2 |
| Silica, mg/L | -- | 27.9 | 30.0 | 24.3 | 27.0 | 29.0 | 48.0 | -- |
| Alkalinity, mg/L | -- | 169.7 | 50.0 | 130.0 | 180.0 | 210.0 | 310.0 | -- |
| Inorganic Nitrogen, mg/L | -- | 8.2 | 0.1 | 3.2 | 6.0 | 11.5 | 35.0 | 10 |
| Arsenic, ug/L | -- | 2.1 | 1.0 | 1.0 | 2.0 | 3.0 | 4.0 | 10 |
| Boron, ug/L | -- | 64.0 | 20.0 | 30.0 | 50.0 | 87.5 | 170.0 | -- |
| Cadmium, ug/L | -- | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 | 10.0 | 5 |
| Chromium, ug/L | -- | 2.0 | 0.0 | 0.0 | 0.0 | 0.0 | 10.0 | 100 |
| Copper, ug/L | -- | 6.0 | 0.0 | 0.0 | 0.0 | 0.0 | 70.0 | 1000 |
| Iron, ug/L | -- | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 | 0.7 | 300 |
| Lead, ug/L | -- | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 15 |
| Manganese, ug/L | -- | 39.3 | 0.0 | 0.0 | 0.0 | 10.0 | 420.0 | 50 |
| Selenium, ug/L | -- | 3.1 | 0.0 | 0.0 | 1.0 | 2.5 | 25.0 | 50 |
| Zinc, ug/L | -- | 111.3 | 10.0 | 20.0 | 50.0 | 105.0 | 620.0 | 5000 |

--, indicates not available

**Table 6.** Summary statistics for groundwater-quality data for 19 samples collected by the Oklahoma Water Resources Board, 2015.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mg/L, milligrams per liter; ug/L, micrograms per liter]

| Parameter | Detection limit | Mean | Min | Percentile | | | Max | EPA Standard |
|---|---|---|---|---|---|---|---|---|
| | | | | 25 | 50 | 75 | | |
| Specific Cond., µS/cm | -- | 624.1 | 298.4 | 403.9 | 556.7 | 717.3 | 1,374.2 | -- |
| Temperature, °C | -5.0 | 18.7 | 16.6 | 17.6 | 18.5 | 19.8 | 21.7 | -- |
| pH, standard unit | -- | 7.0 | 6.4 | 6.9 | 7.1 | 7.2 | 7.2 | -- |
| Dissolved Solids, mg/L | 10.0 | 387.5 | 183.0 | 263.5 | 323.0 | 446.0 | 826.0 | 500 |
| Calcium, mg/L | 0.5 | 74.3 | 34.6 | 48.4 | 64.8 | 91.8 | 156.0 | -- |
| Magnesium, mg/L | 0.5 | 16.4 | 5.8 | 8.7 | 12.0 | 20.1 | 43.7 | -- |
| Sodium, mg/L | 0.5 | 28.1 | 10.2 | 15.5 | 21.0 | 35.9 | 99.7 | -- |
| Potassium, mg/L | 0.5 | -- | < | < | 2.6 | 3.8 | 6.2 | -- |
| Sulfate, mg/L | 10.0 | 59.6 | 11.9 | 18.9 | 38.7 | 62.0 | 250.0 | 250 |
| Chloride, mg/L | 10.0 | 40.6 | < 10.0 | 16.2 | 26.0 | 40.7 | 173.0 | 250 |
| Bicarbonate, mg/L | 12.0 | 226.0 | 81.0 | 154.5 | 203.0 | 310.0 | 397.0 | -- |
| Fluoride, mg/L | 0.2 | -- | < | < | < | 0.4 | 0.6 | 2 |
| Silica, mg/L | 0.05 | 30.3 | 24.2 | 26.2 | 27.8 | 32.7 | 42.8 | -- |
| Alkalinity, mg/L | 10.0 | 182.6 | 66.0 | 125.5 | 165.5 | 254.0 | 325.0 | -- |
| Inorganic Nitrogen, mg/L | 0.05 | 8.4 | 0.8 | 5.3 | 7.3 | 10.2 | 20.8 | 10 |
| Arsenic, ug/L | 1.0 | 2.4 | < | 1.5 | 2.2 | 3.5 | 4.6 | 10 |
| Boron, ug/L | 20.0 | 67.4 | < | 34.1 | 61.4 | 71.3 | 241.0 | -- |
| Cadmium, ug/L | 0.5 | -- | -- | -- | -- | -- | -- | 5 |
| Chromium, ug/L | 1.0 | -- | < | < | 2.1 | 5.8 | 12.3 | 100 |
| Copper, ug/L | 1.0 | -- | < | < | 2.3 | 3.6 | 8.8 | 1000 |
| Iron, ug/L | 20.0 | -- | < | < | < | < | 29.4 | 300 |
| Lead, ug/L | 0.5 | -- | < | < | < | 0.8 | 1.0 | 15 |
| Manganese, ug/L | 5.0 | -- | < | < | < | < | 0.1 | 50 |
| Selenium, ug/L | 1.0 | -- | < | < | 2.6 | 3.8 | 6.2 | 50 |
| Zinc, ug/L | 5.0 | -- | < | < | 25.2 | 28.4 | 139.0 | 5000 |

--, indicates not available

<, indicates concentration is less than the minimum reported detection limit.

## SUMMARY

Oklahoma groundwater law requires the Oklahoma Water Resources Board to make a tentative determination of the maximum annual yield of each groundwater basin based on the following:

1. The total land area overlying the basin or subbasin;
2. The amount of water in storage in the basin or subbasin;
3. The rate of recharge to and total discharge from the basin or subbasin;
4. Transmissivity of the basin or subbasin; and
5. The possibility of pollution of the basin or subbasin from natural sources.

The Oklahoma Water Resources Board has, based on information from the USGS and the Board, made the following determinations:

<u>Beaver-North Canadian River Alluvium and Terrace Groundwater Basin (Reach I)</u>

1. Total land overlying the basin was determined to be 545,863 acres or 853 square miles.

2. The total amount of water in storage in Reach I in 2011 was determined to be about 3.1 million acre-feet based on the sum of model cell storage values calculated from the multiplication of cell area, cell saturated thickness, and cell specific yield.

3. The rate of natural recharge to the basin is about 143,136 acre-feet per year, which based on the overlying land area of the basin is equivalent to about 3.15 inches per year.

4. Total anthropogenic discharge (allocated water rights) from the basin was calculated to be about 94,341.7 acre-feet/year or about 1,886,834 acre-feet of water over the 20-year Life of the basin.

5. Values of transmissivity within the basin range from 0 to 8,030 square feet per day, with a mean of around 1,780 feet squared per day.

6. Nitrogen (as nitrate) is considered a water quality concern in Reach I of the Beaver-North Canadian River Alluvial and Terrace Groundwater Basin, specifically in areas overlain by croplands.

7. The MAY percent developed for the basin was calculated to be between 32–41 percent based on the total allocated rights (prior and regular); therefore, EPS allocations for new permits will not be eligible for delayed or gradual implementation.

8. The maximum annual yield ranges from 228,940 to 288,888 acre-feet per year, equivalent to an EPS range between 0.48 to 1.20 (acre-feet/acre)/year for the undeveloped land area. Current active regular permits will maintain an equal proportionate share of 1.00 (acre-feet/acre)/year based on the August 1983 final order. If the Board elects to use the full depletion scenario, the EPS rate for both developed and undeveloped land would be 1.12 (acre-feet/acre)/year to maintain the same maximum annual yield. If the Board elects to use the 1983 final order EPS rate, the equivalent MAY volume would be about 266,408 acre-ft/year. The Board subcommittee selected an EPS rate of 0.5 (acre-feet/acre)/year, equivalent to a MAY volume of 234,011 acre-feet/year.

**Figure 1.** Map showing saturated thickness at the end of transient model simulation 5 (1957–1973) in the alluvium and terrace aquifer along the Beaver-North Canadian River, Northwestern Oklahoma (Davis and Christenson, 1981).

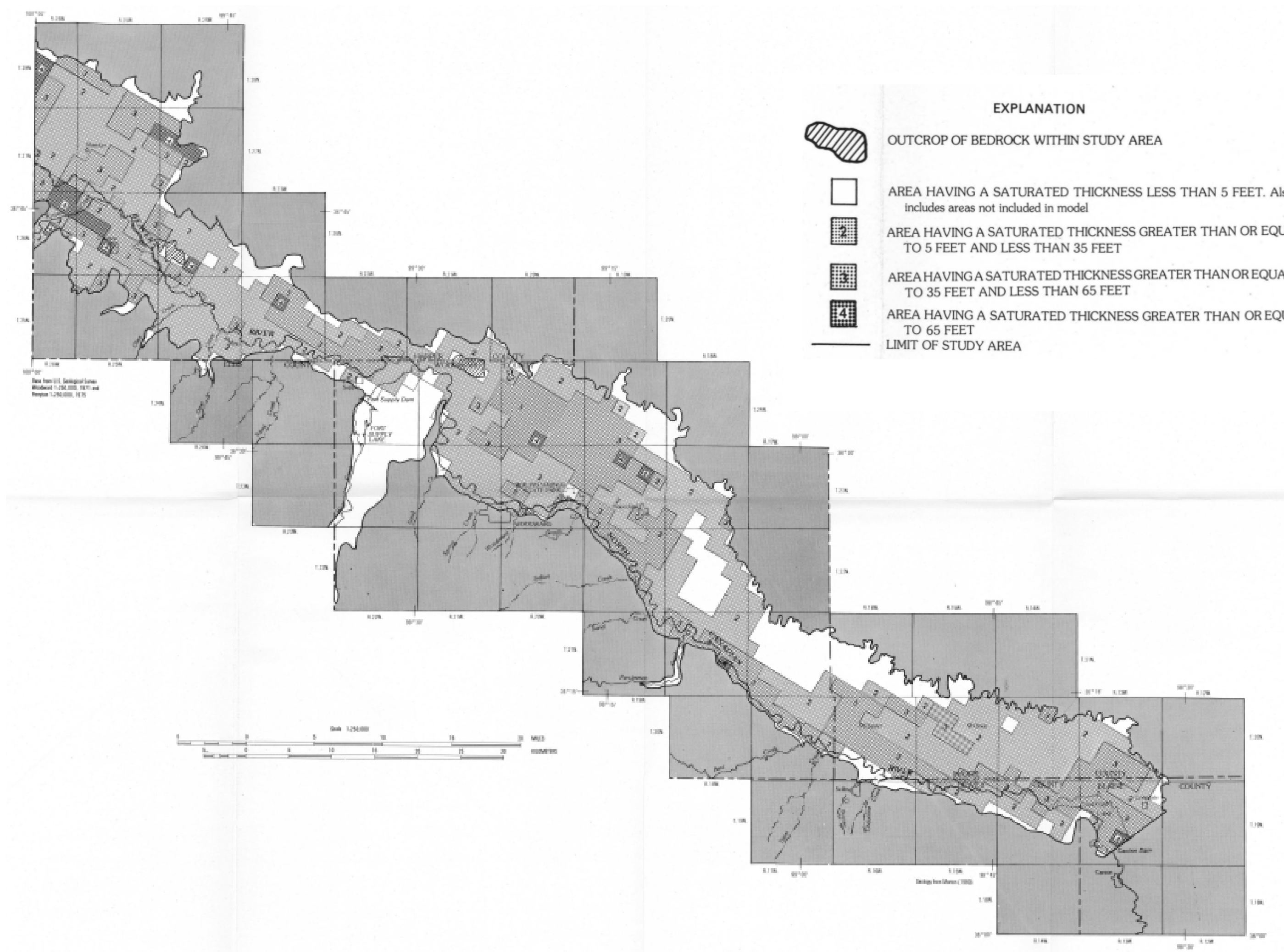


**Figure 2.** Map showing areas excluded from groundwater flow model simulations because of a purported lack of flow or little (less than 5 feet) or no saturation. Areas were digitized from plates 5, 7, and 13 in Davis and Christenson (1981).

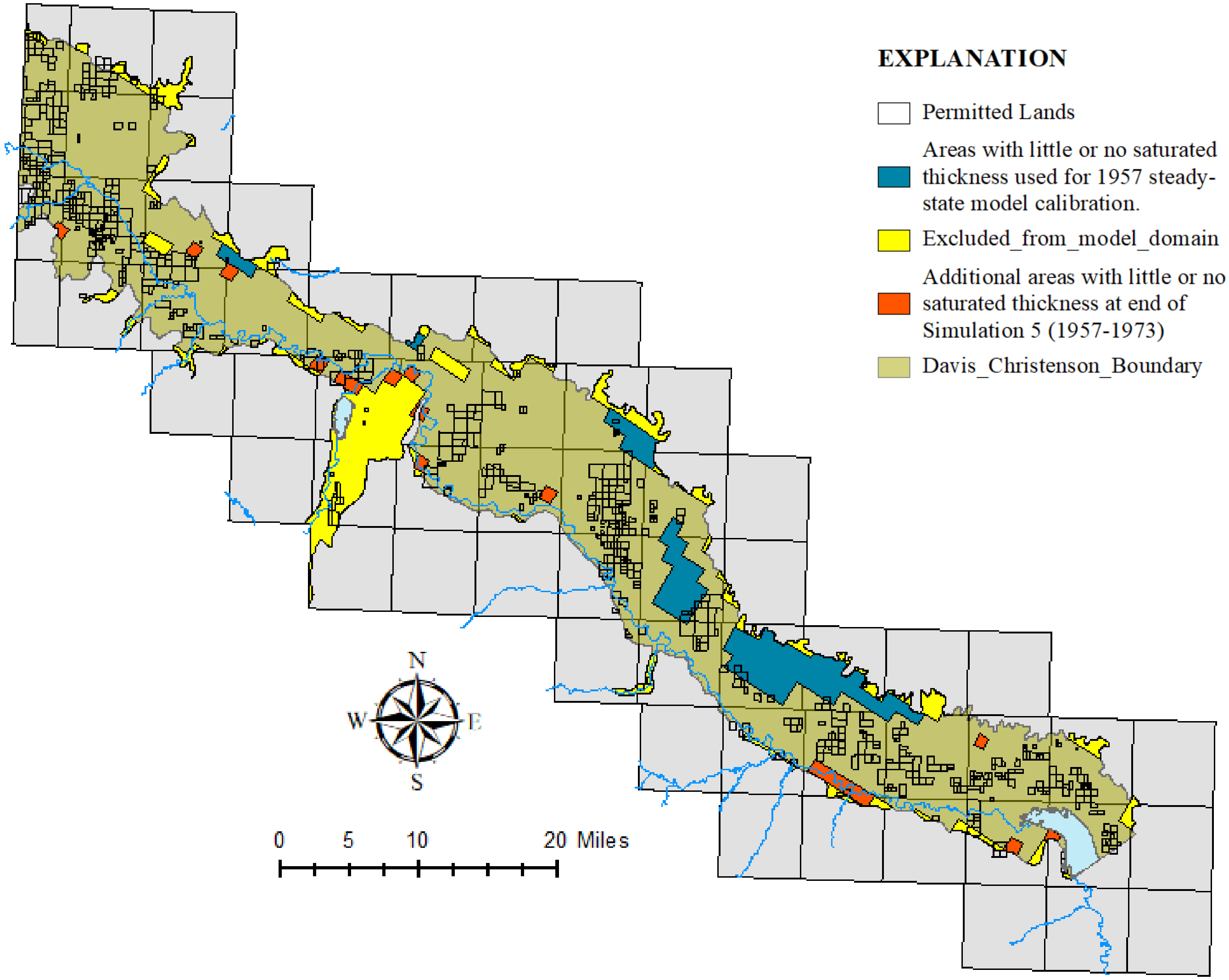
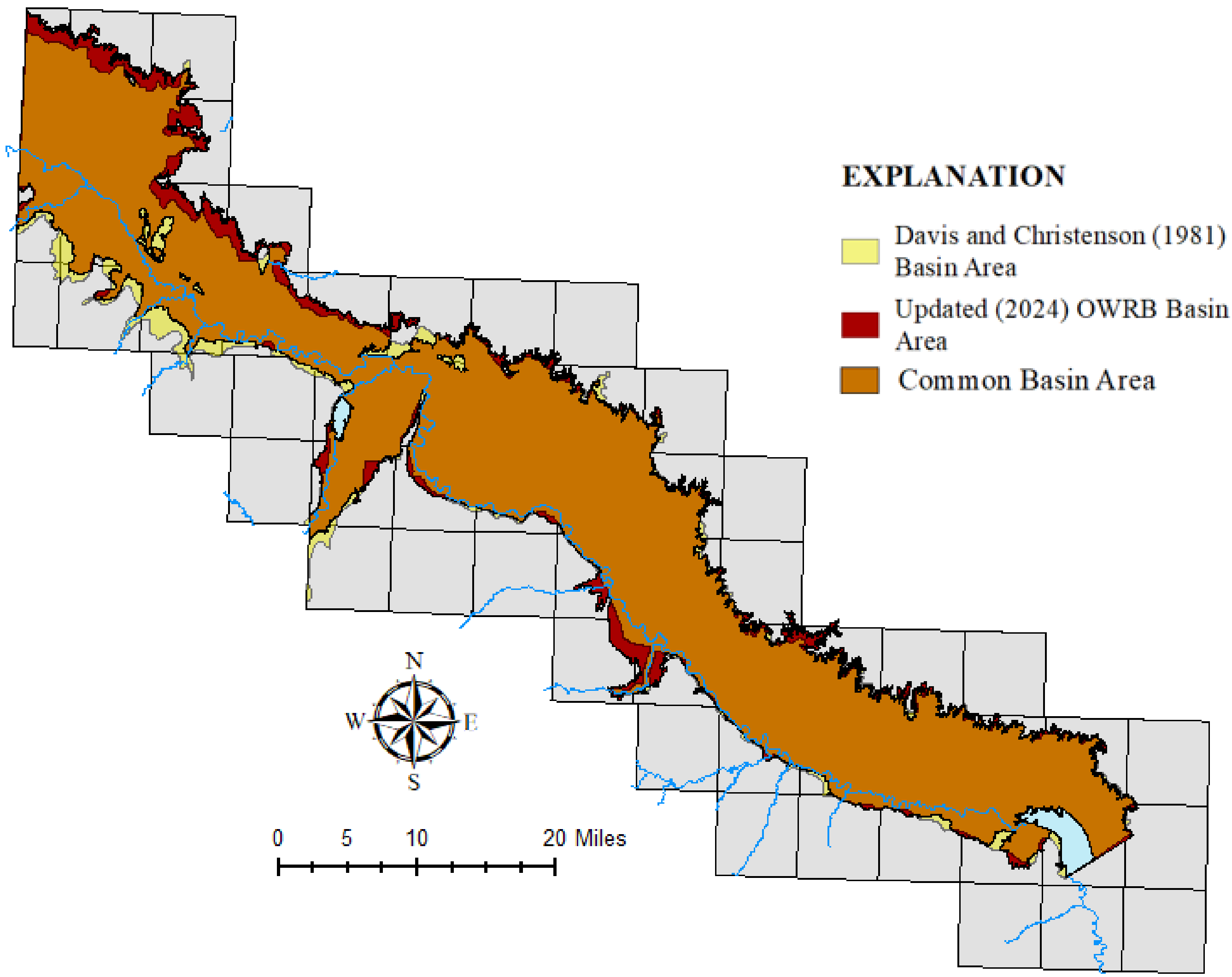


**Figure 3.** The 1983 final order groundwater basin of the Beaver-North Canadian River Alluvium and Terrace Aquifer (yellow region) and revised OWRB groundwater basin area (red region); common basin area shown in orange region.



## Supplemental

The aquifer base and potentiometric surface were reevaluated using data from the OWRB well drillers database as part of a post-report analysis**. Figure S1** shows the USGS aquifer base (bottom) and the reevaluated OWRB aquifer base (top). **Figure S2** shows a residual map of the two aquifer base maps, with negative values indicating the OWRB base is below the USGS base and positive values indicating the OWRB base is above the USGS base. The differences between the two maps varied from +200 feet to -100 feet, with a mean of 4.5 feet and a standard deviation of 31 feet. The large changes in Harper County are attributed to revised base picks from 183 drillers' reports — all logs contained lithologic descriptions (most commonly "red bed") indicating the Tertiary-Permian geologic contact.

**Figure S3** shows the USGS potentiometric surface (bottom) and the reevaluated OWRB potentiometric surface (top). The 160 well sites (117 in Reach I) used in the 2012 water-level synoptic were used for the OWRB reevaluation, and additional data from the OWRB drillers' database. **Figure S4** shows a residual map of the two potentiometric surface maps, with negative values indicating the OWRB potentiometric surface was below the USGS potentiometric surface and positive values indicating the OWRB potentiometric surface was above the USGS potentiometric surface. Differences between the two potentiometric surface maps varied from +83 to -82, with a mean of 0.4 feet, and a standard deviation of 16 feet. Excluding areas near the edges of the defined basin or previously mapped bedrock outcrops, the largest change in Major County is attributed to 47 supplemental depth-to-water measurements from drillers' reports — the measurements were taken during different years but provided a general depth to the water table in an area that had insufficient synoptic measurements to map the surface in greater detail. Wells drilled in this region of the basin generally target the underlying Marlow Formation because the terrace sands are unsaturated.

**Figure S5** shows the USGS saturated thickness map (bottom) and the reevaluated OWRB saturated thickness map (top). The most apparent difference is in Harper County, where the Ogallala Formation is present. The USGS saturated thickness map has a larger area greater than 120 feet thick that is not well supported by drillers' logs, the Davis and Christenson (1981) report, or the USGS report on the saturated thickness of the High Plains Aquifer by McGuire and others (2012). The OWRB saturated thickness map shows a narrower valley of high saturated thickness near the current day Beaver-North Canadian River that may represent a pre-Pliocene paleo-channel or series of collapse features that extend into the Panhandle. The relatively thick, semi-circular saturated thickness areas northeast of the river may be attributed to pre-Pliocene collapse features that were infilled with Ogallala or Laverne Formation deposits (Myers, 1959; Davis and Christenson, 1981). **Figure S6** shows the potentiometric surface (bottom) and base (top) maps digitized from the Davis and Christenson (1981) report.

**Table S1** lists the EPS rates and cumulative volumes of water recovered (pumped) during each life of the basin simulation period for the unmodified USGS numerical flow model and the calibrated OWRB analytical model (under normal recharge). Model calibration was performed to refine input coefficients so that the depletion curves derived from each model were similar for each life of the basin period. The refined input coefficients were then used to estimate EPS rates and MAY volumes for the two pumping scenarios based on changes to the basin boundary, base, and potentiometric surface by the OWRB.

**Table S1.** EPS rates and cumulative volumes of water recovered during each life of basin simulation period for the unmodified USGS numerical flow model and calibrated OWRB analytical model.

| Period (years) | USGS EPS Rate | OWRB EPS Rate | USGS cumulative volume pumped | OWRB cumulative volume pumped | Percent difference |
|---|---|---|---|---|---|
| 20 | 0.57 | 0.57 | 4,508,960.25 | 4,509,215.62 | 0.006 |
| 40 | 0.54 | 0.54 | 8,158,146.54 | 8,158,924.83 | 0.010 |
| 50 | 0.53 | 0.53 | 9,660,762.87 | 9,660,451.52 | 0.003 |

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**Figure S1.** The USGS aquifer base map (bottom) and reevaluated OWRB aquifer base map (top). Both maps used the same altitude intervals shown in the top figure.

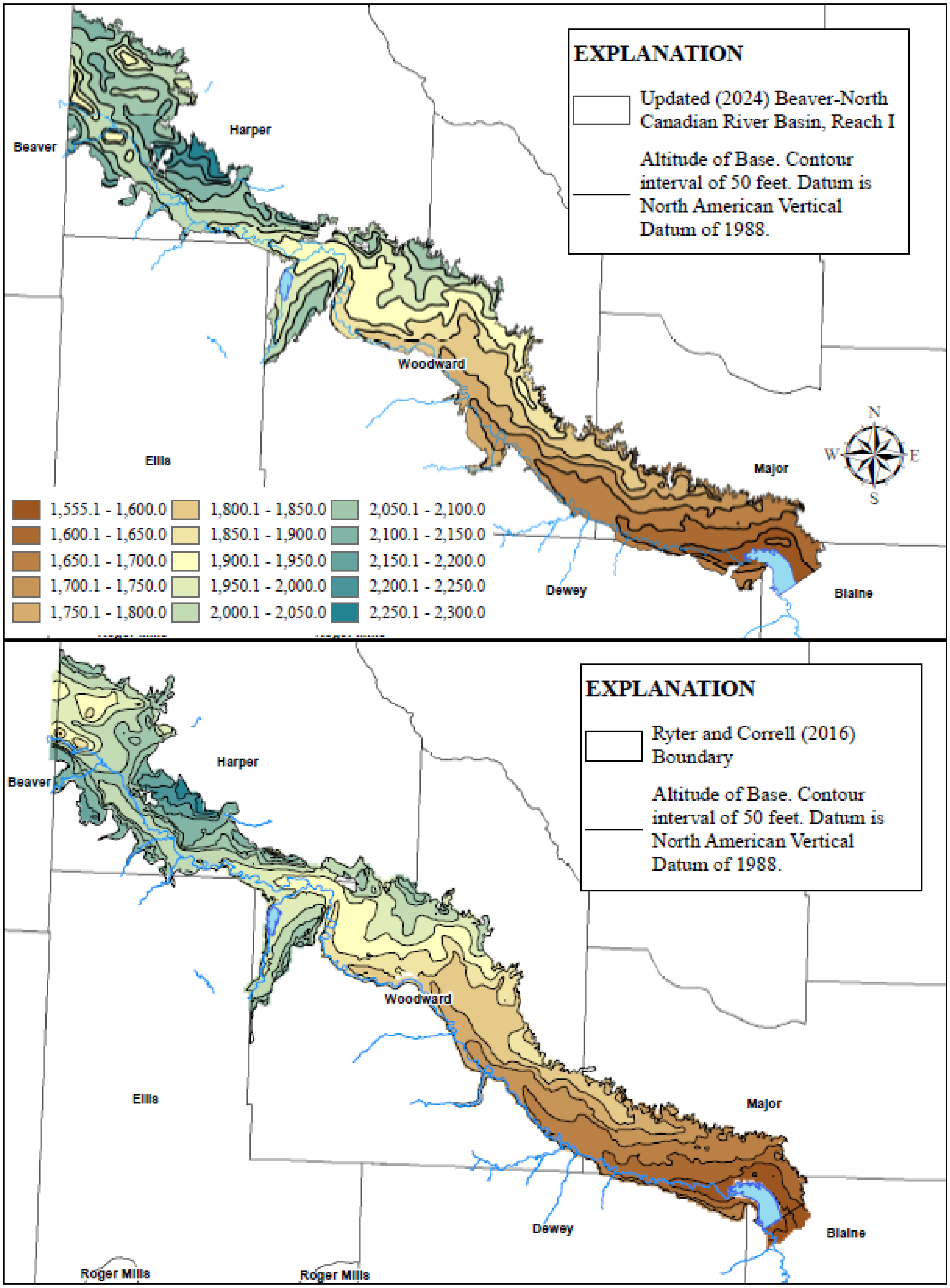

**Figure S2.** Residual map for the OWRB base aquifer minus the USGS aquifer base. Negative values indicate the OWRB base is below the USGS base and positive values indicate the OWRB base is above the USGS base. The average difference between the two base maps is 4.5 feet.

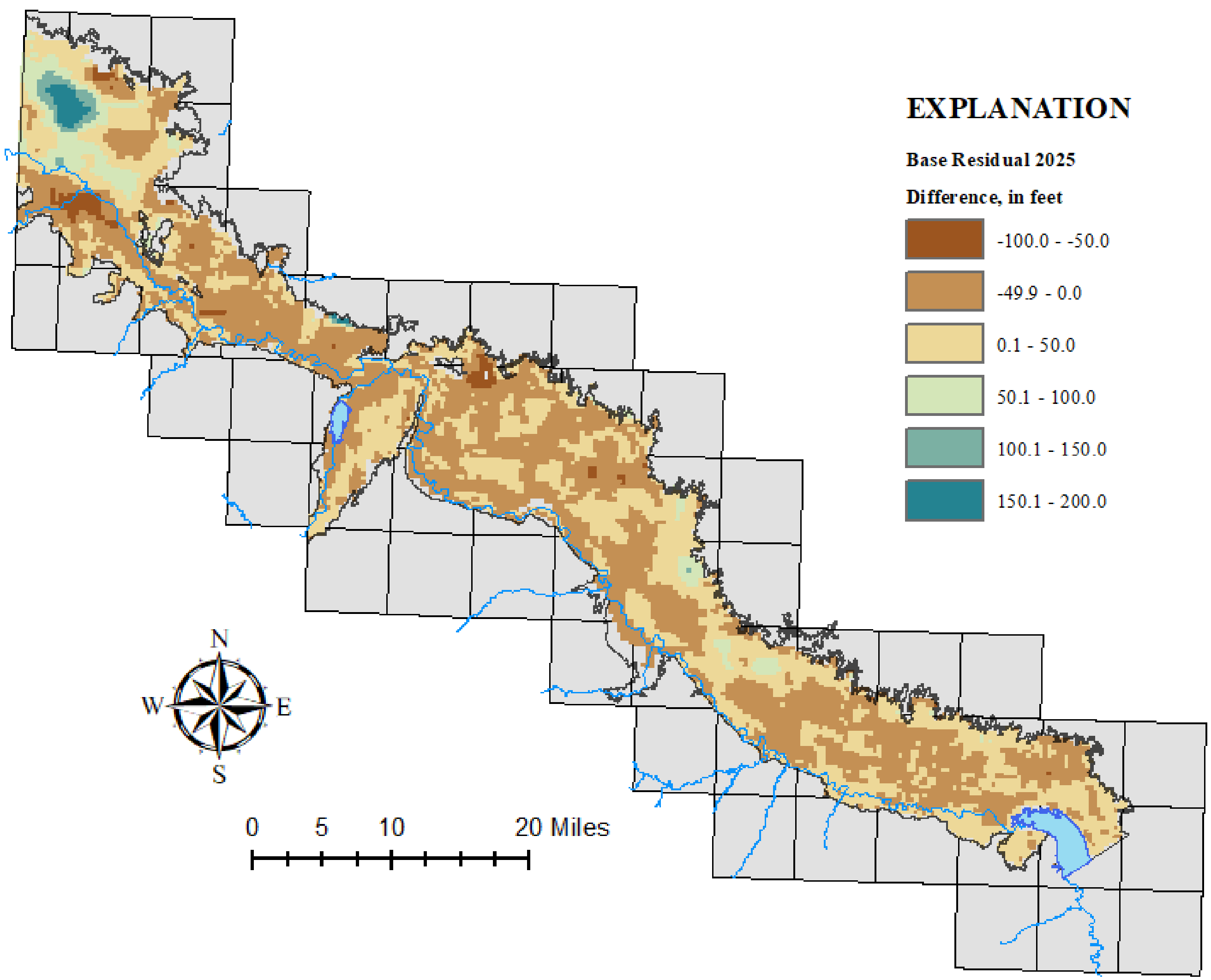

**Figure S3.** The USGS potentiometric surface map (bottom) and reevaluated OWRB potentiometric surface map (top). Both maps used the same altitude intervals which is only shown in the top figure.

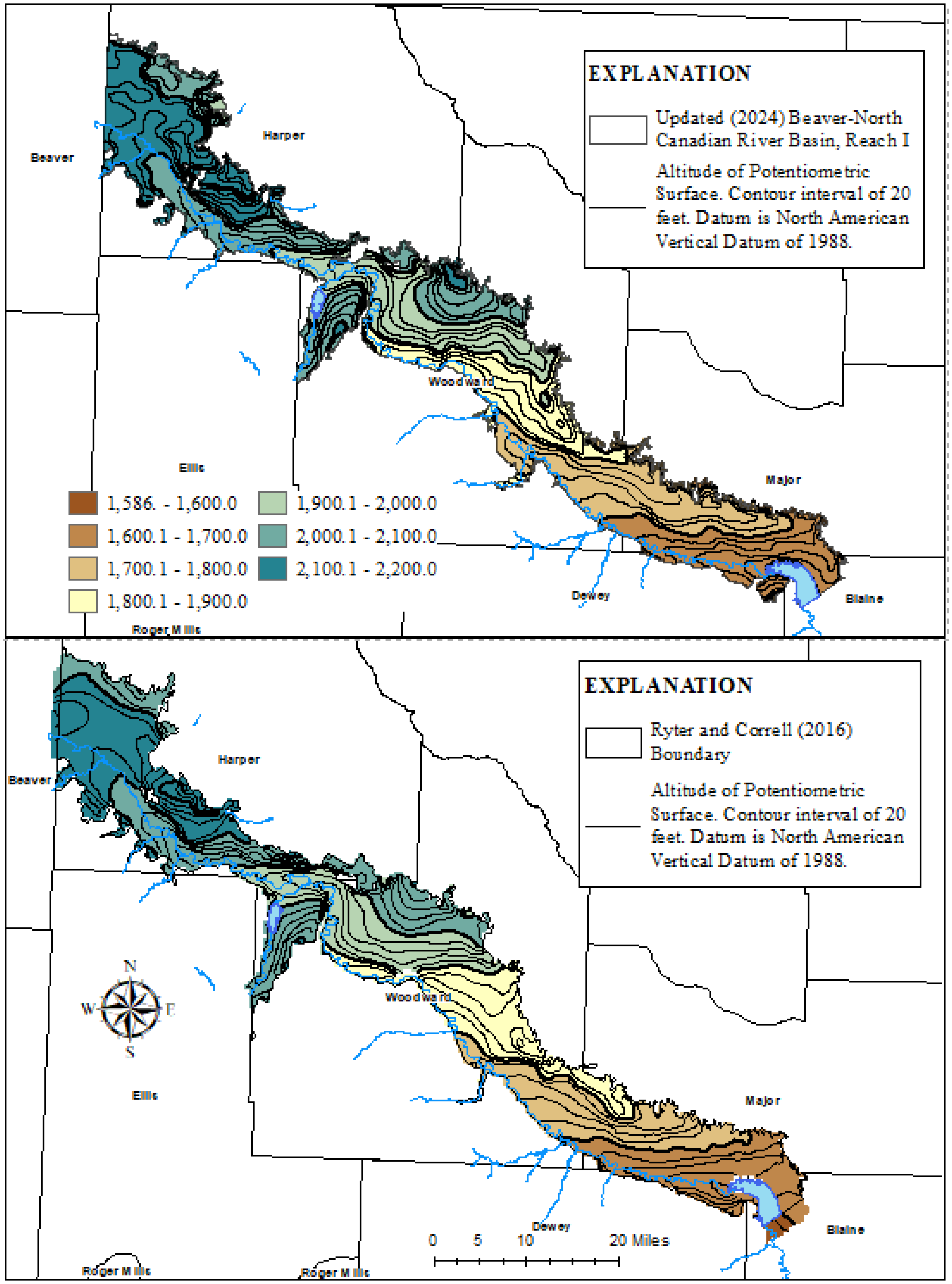

**Figure S4.** Residual map for the OWRB potentiometric surface minus the USGS potentiometric surface. Negative values indicate the OWRB potentiometric surface is below the USGS POT, and positive values indicate the OWRB potentiometric surface is above the USGS POT. The average difference between the two base maps is 1.5 feet.

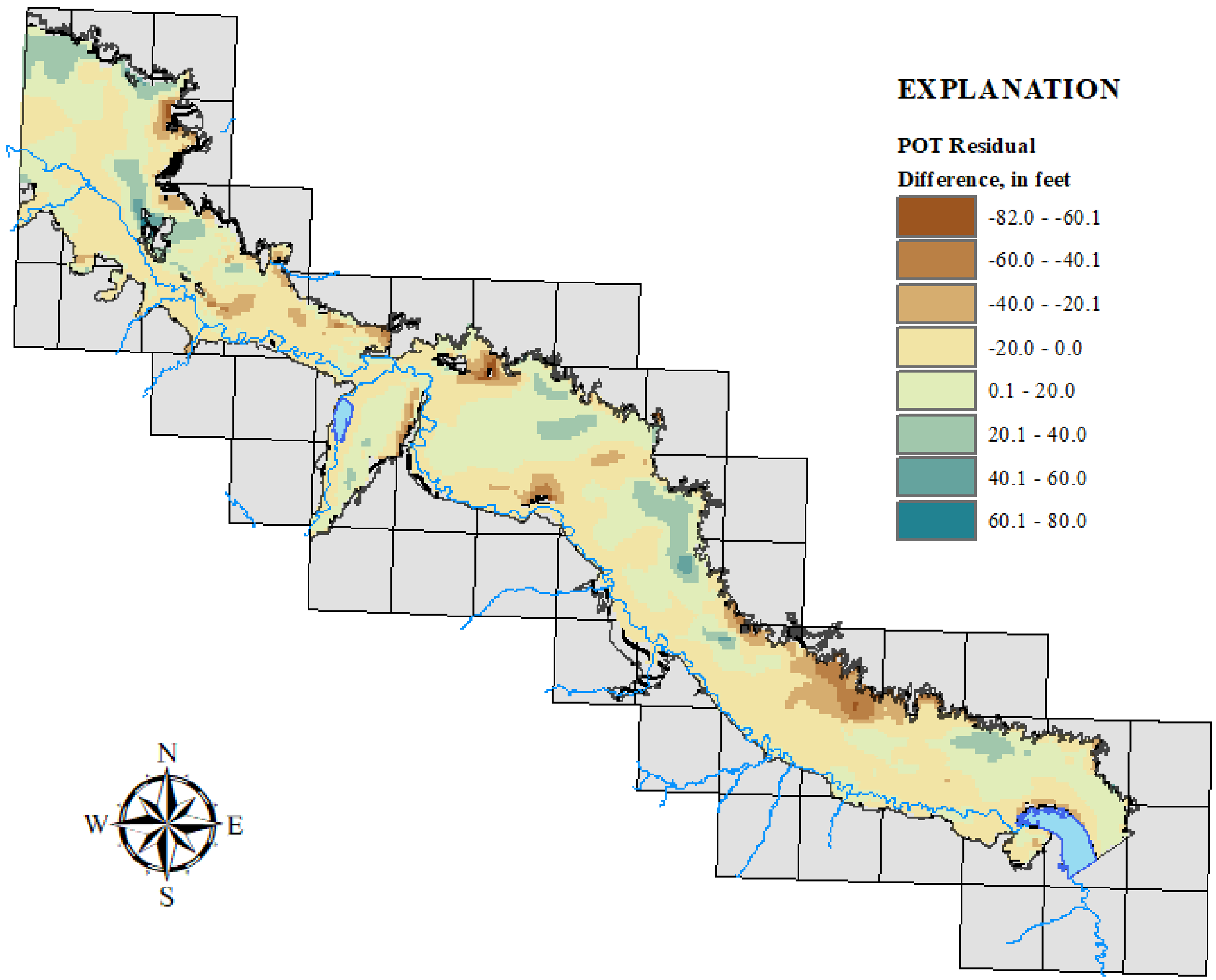

**Figure S5.** The OWRB saturated thickness map (top) and 2016 USGS saturated thickness map (bottom).

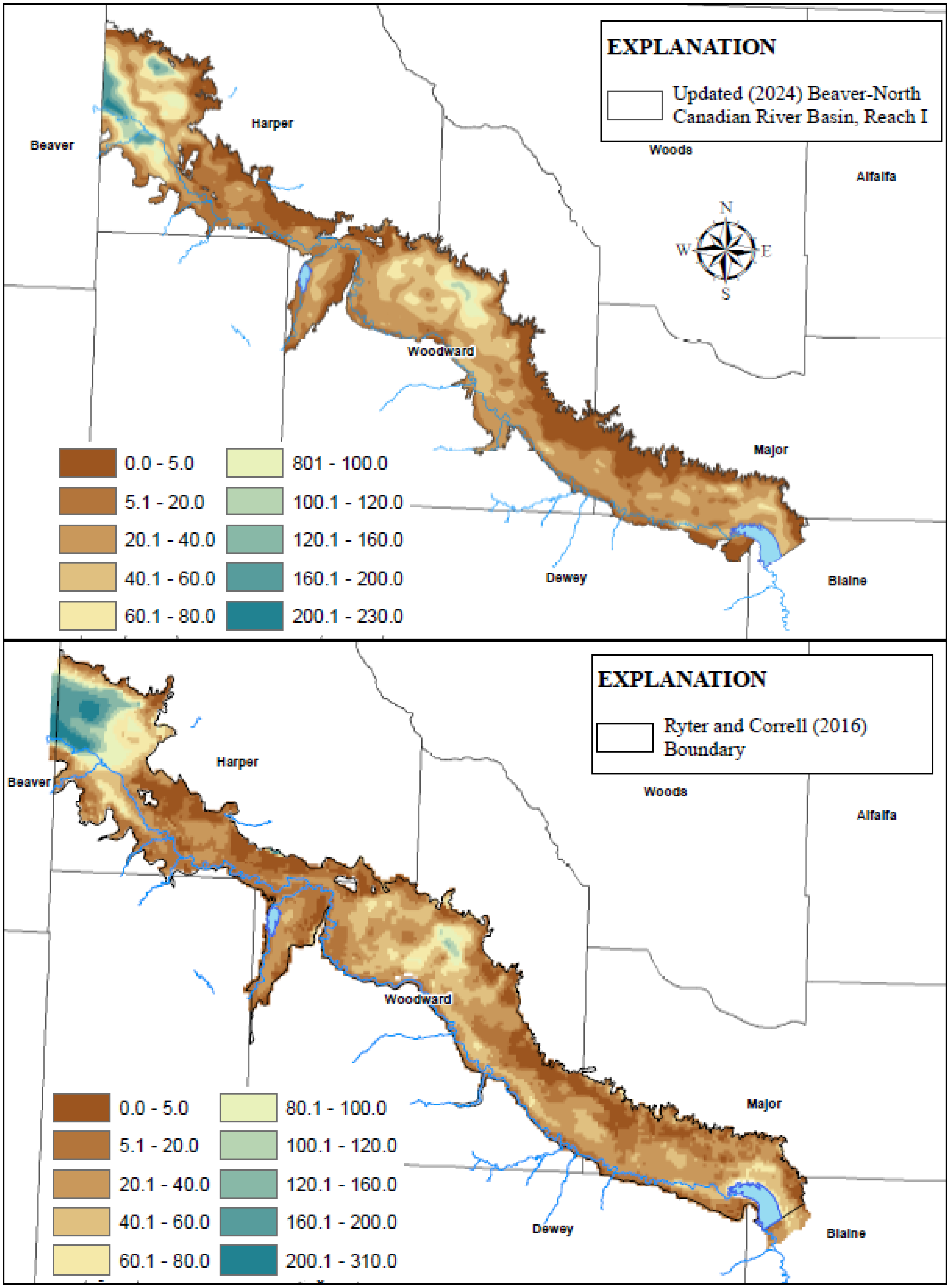

**Figure S6.** The Davis and Christenson (1981) base map (top) and potentiometric surface map (bottom). The maps use the same altitude intervals as the USGS and OWRB maps in Figures S1 and S3.

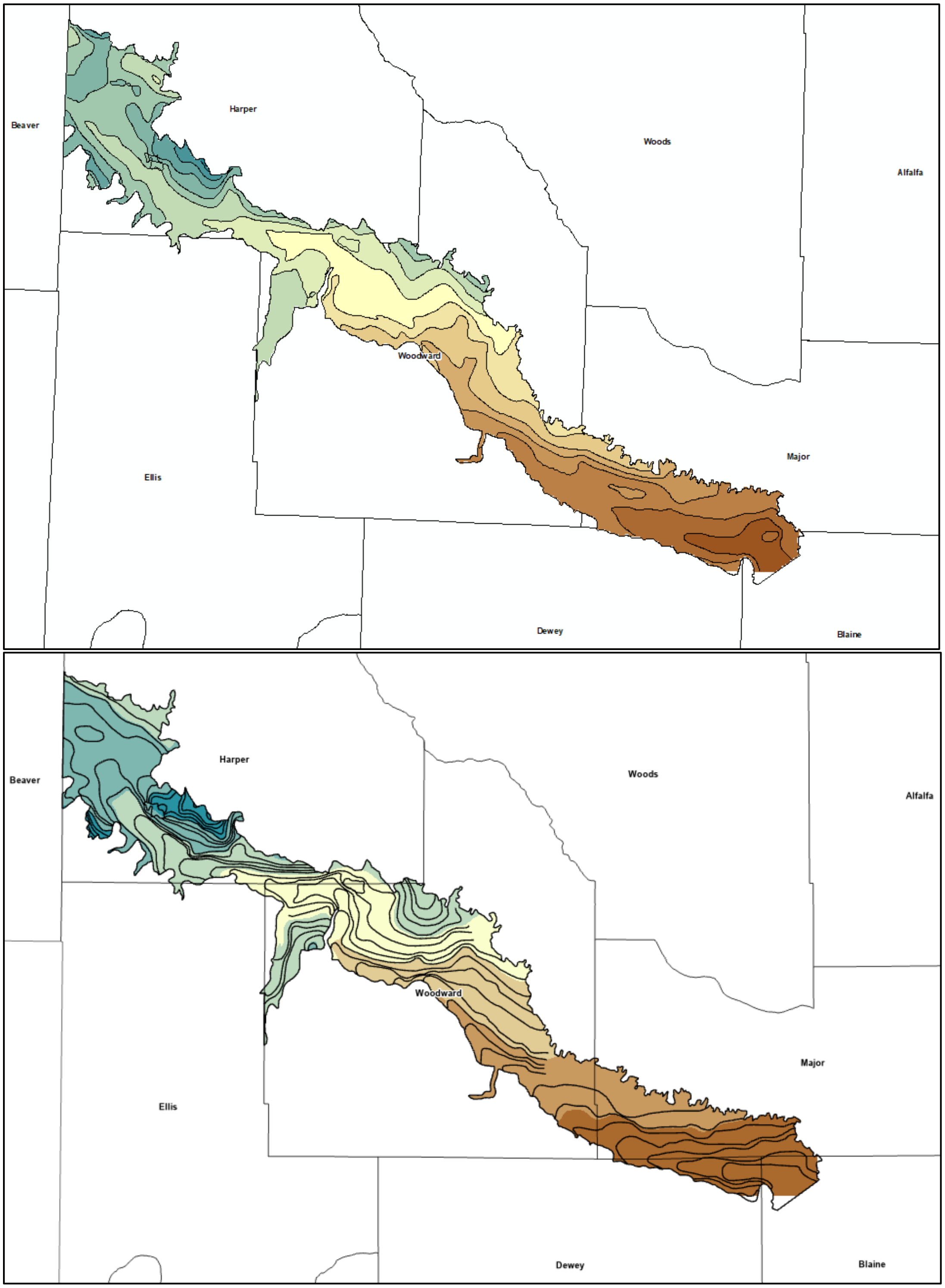

**Figure S7.** Plate 3 map from Davis and Christenson (1981) showing the potentiometric surface of the alluvium and terrace aquifer during 1977-1978 along the Beaver-North Canadian River, Northwestern Oklahoma. Included herein to show why some contours just end in **Figure S6**.