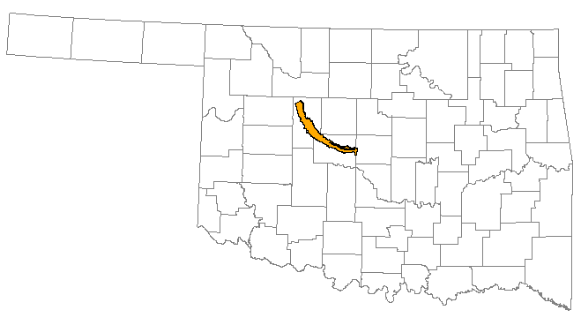
40-YEAR UPDATE

MAXIMUM ANNUAL YIELD DETERMINATION

FOR THE

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

Executive Summary Report



Oklahoma Water Resources Board
Water Rights Administration Division
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August 22, 2025

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 April 10, 1990, a final order for Reach II 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 data and information provided in the U.S. Geological Survey [USGS] Water Resources Investigation Report 83-4076 entitled Numerical Simulation of the Alluvium and Terrace Aquifer along the North Canadian River from Canton Lake to Lake Overholster, Central Oklahoma (Christenson, 1983).

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 II) underlies approximately 232,035 acres (362.6 square miles [mi^2]) of land along approximately 116 miles of the North Canadian River in northwestern Oklahoma, extending from Canton Lake Dam in northwestern Blaine County to Lake Overholster on the west side of Oklahoma City.

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. In Canadian County, bedrock outcrops in a narrow band approximately 22 miles long that separates the alluvial deposits from the older and topographically higher terrace deposits.

- The saturated thickness of the groundwater basin can vary from less than a foot to a maximum of about 70 feet. The average saturated thickness of Reach II as determined at the end of the 1980–2011 transient model period was about 28 feet (including model cells with a saturated thickness of zero [dry cells]). The aquifer base and potentiometric surface were reevaluated, resulting in a mean saturated thickness of 24 feet (including dry cells).

- Three (3) published aquifer tests from Canadian County (all in alluvium) yielded transmissivity values of 5,347.2, 8,020.8, and 13,100.7 square feet per day (ft^2/day), respectively (Mogg and others, 1960). The transmissivity estimates are equivalent to hydraulic conductivity values of 162, 191, and 545.9 feet per day (ft/day), respectively. Mogg and others (1960) posed that an average transmissivity of about 7,352 ft^2/day may be representative of the alluvium deposits. The Christenson (1983) model transmissivities ranged from 0 to 2,050 ft^2/day with a mean of 1,080 ft^2/day. Model-calibrated horizontal hydraulic conductivity ranged from 4 to 279 feet per day (ft/day), with a mean of 92 ft/day.

- Model-calibrated specific yield ranged from 0.10 to 0.25, with a mean of 0.20[1]. 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 82,400 acre-ft/year in Reach II (4.18 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 II model calibrations resulted in a smaller mean annual recharge estimate of 60,950 acre-ft/year (3.1 in/year) for the same period within the 369 mi^2 model area[2]; when adjusted to the OWRB-defined basin area (see *Changes in Basin Area* subsection), the mean annual recharge is approximately 59,942 acre-ft/year.

- The total amount of available groundwater in storage estimated from the USGS model files was about 1.28 million acre-feet in 2011 (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 1.1 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 larger than the 950,000 acre-feet estimated in the 1983 hydrologic investigation because of the smaller (0.16) specific yield estimate used for that model. The OWRB volume is less than the USGS volume because of reduced saturated thicknesses in Blaine and Canadian counties.

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1. 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 II was 0.20. Likewise, the initial estimates of Kh were taken from ranges published by Fetter (1994).

2. The report lists the model area for Reach II as approximately 371 square miles (3,843 model cells). However, when the model files were imported into ArcGIS, the number of model cells was determined to be 3,825, equivalent to an area of about 369 square miles.

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: *"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: *"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 II 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 II, 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 II of the Beaver-North Canadian River Alluvium and Terrace Groundwater Basin, northwestern Oklahoma (Ryter and Correll, 2015).

Period (years)	Reach II applied EPS pumping rates		
	Recharge reduced by 10 percent	No change in recharge	Recharge increased by 10 percent
20	0.69	0.73	0.77
40	0.57	0.61	0.65
50	0.60	0.61	0.67
	Reach II MAY volumes (from model)		
20	123,913	130,454	138,034
40	99,064	106,042	113,112
50	98,874	106,258	113,628

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; contours were added or adjusted to add more control over the interpolation process. 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 II 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 II 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 II EPS pumping rates (Final applied rate)		
	Recharge reduced by 10 percent	No change in recharge	Recharge increased by 10 percent
20	0.66	0.69	0.72
40	0.55	0.58	0.61
50	0.55	0.58	0.61
	Reach II MAY volumes (from model)		
20	115,697.17	120,643.56	125,589.94
40	94,276.27	98,923.86	103,571.45
50	94,406.21	99,013.93	103,621.62
	Reach II EPS pumping rates (After removal of prior rights)		
20	0.46	0.50	0.54
40	0.34	0.38	0.41
50	0.34	0.38	0.41
	Reach II MAY volumes (After removal of prior rights)		
20	55,309.07	60,255.46	65,201.84
40	33,888.17	38,535.76	43,183.35
50	34,018.11	38,625.82	43,233.52

An EPS rate of 0.69 (acre-feet/acre)/year and a MAY volume[3] of 120,643.56 acre-feet/year were estimated from the updated OWRB analytical model for the 20-year basin life. To accommodate the 127 prior rights and ensure they are adequately protected, 27,402.1 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 93,241.46 acre-feet/year. As of the date of this report, there are 177 active regular groundwater-use permits within Reach I. Collectively, these permits constitute a total annual allocation of 32,986.0 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 60,255.46 acre-ft/year. The final EPS rate for the undeveloped lands was determined to be 0.50 (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 1990 final order. To note, the full depletion scenario was not statutorily permitted until 1994. Unlike the Reach I numerical flow model by Davis and Christenson (1981), the Christenson (1983) numerical flow model for Reach II did not arrive at an EPS rate of 1.0 (acre-feet/acre)/year, but rather ran the model assuming water would be withdrawn at a rate sufficient to irrigate every acre of land within a node at a rate of 1.0 (acre-feet/acre)/year.

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.

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 II 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 II EPS pumping rates (Final applied rate)		
	Recharge reduced by 10 percent	No change in recharge	Recharge increased by 10 percent
20	0.77	0.80	0.84
40	0.63	0.66	0.69
50	0.62	0.65	0.69
	Reach II MAY volumes (from model)		
20	120,137.97	124,862.60	129,227.23
40	94,824.49	98,985.25	103,146.02
50	94,315.07	98,432.71	102,550.35
	Reach II EPS pumping rates (After removal of prior rights)		
20	0.59	0.63	0.67
40	0.43	0.47	0.50
50	0.42	0.46	0.50
	Reach II MAY volumes (After removal of prior rights)		
20	59,749.87	64,294.50	68,839.13
40	34,436.39	38,597.15	42,757.92
50	33,926.97	38,044.61	42,162.25

An EPS rate of 0.80 (acre-feet/acre)/year and a MAY volume of 124,862.60 acre-feet/year were estimated from the OWRB analytical model for the 20-year basin life. To accommodate the 127 prior rights and 177 active regular groundwater-use permits in Reach I and ensure they are adequately protected, 60,388.10 acre-feet of water rights were removed from the model-derived MAY, reducing the volume to 64,294.50 acre-ft/year. The final EPS rate for the undeveloped lands was determined to be 0.63 (acre-feet/acre)/year based on the model-derived MAY and existing dedicated lands permitted at 1.0 (acre-feet/acre)/year. Differences between the USGS model EPS rates and those determined from the OWRB analytical model speak to the sensitivity of each model to parameterization and mass balance approaches.

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. The analytical calculator was modified to allow for changes in recharge and to account for permits with a final order EPS rate.

Table 4. Equal-proportionate-share rates for select life of basin periods in Reach II 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	0.58	0.61	0.65
40	0.45	0.48	0.52
50	0.42	0.46	0.49
	Reach I MAY volumes (from model)		
20	97,653.69	103,647.93	109,642.16
40	75,800.91	81,795.15	87,789.39
50	71,430.36	77,424.60	83,418.73
	Reach I EPS pumping rates (After removal of prior rights)		
20	0.37	0.41	0.45
40	0.22	0.26	0.30
50	0.19	0.23	0.27
	Reach I MAY volumes (After removal of prior rights)		
20	37,265.59	43,259.83	49,245.06
40	15,412.81	21,407.05	27,401.29
50	11,042.26	17,035.60	23,030.73

An EPS rate of 0.61 (acre-feet/acre)/year and a MAY volume of 103,647.93 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, 60,388.10 acre-feet was removed from the model-derived MAY, reducing the volume to 43,259.83 acre-feet/year. The final EPS rate for the undeveloped lands was determined to be 0.41(acre-feet/acre)/year, with existing dedicated lands permitted at 1.0 (acre-feet/acre)/year.

Changes in Groundwater Basin Area

The 1990 final order for the Beaver-North Canadian River Alluvium and Terrace Groundwater Basin (Reach II) established a groundwater basin area of about 211,840 acres (331 mi^2); the basin area was defined within the final order under Findings of Fact 8 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 a calibrated transient flow simulation for the period 1940–1973 (**Figure 1**; Plate 8 in Christenson, 1983), which used a constant recharge rate of one (1) inch per year, an average specific yield of 0.16, 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 39.6 mi^2 (25,319 acres) of the study area[4] were excluded from the model domain purportedly because they had little or no saturated thickness and therefore negligible flow during the steady-state model calibrations (**Figure 2**; yellow areas); the largest of these areas were northwest of the city of Watonga and west of the town of Richland. 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).

4. The study area of Reach II in Christenson (1983) was estimated to be about 400 square miles. However, when digitized in ArcGIS and calculated, the study area was determined to be 373.4 square miles (238,976 acres). Based on Plate 5 in the modeling report, the authors included alluvium and terrace deposits northeast of Canton Lake in T.19N., R.13WI, as well as the outcropping bedrock areas in Canadian County ; the aggregate of these areas with the defined basin boundary was estimated to be about 396 square miles.

At the end of the 1940–1973 calibrated transient flow simulation, an additional 7.2 mi^2 (4,635 acres) of the basin area had a saturated thickness that fell below five (5) feet (**Figure 2**; orange areas), bringing the total area with little or no saturated thickness to about 46.8 mi^2; the subtraction of this area from the study area (373.4 mi^2) results in a groundwater basin area of 326.6 mi^2. Model discretization resulted in some areas of outcropping bedrock being encompassed within saturated model cells at the end of the 1940–1973 transient flow simulation. Consequently, about 3.9 mi^2 of outcropping bedrock was erroneously included in the total groundwater basin area (**Figure 2**; blue areas), which is how the authors of the 1983 model report came to a basin area of 331 mi^2. To note, the groundwater basin area in Christenson (1983) included the area of Canton Lake, which served as a constant head boundary.

For modeling purposes, the updated hydrologic investigation report by Ryter and Correll (2015) included alluvium and terrace deposits adjacent to and south of Lake Overholster in parts of Canadian and Oklahoma counties that were not included in the 1990 final order boundary (**Figure 3**; pink hashed area). As the Reach I executive summary mentioned, the Reach I to Reach II transition line was shifted about 1.9 miles southeast of Lake Canton to avoid boundary conditions within the model. The boundary was defined based on surface geology maps for the Woodward, Clinton, and Oklahoma City hydrologic atlases (Carr and Bergman, 1976; Morton,1980; Bingham and Moore, 1975). The total area of Reach II was about 377.8 mi^2 — excluding Lake Overholster, the total area of Reach II was about 375.4 mi^2. Unlike the 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 II based on updated geology maps for northwestern Oklahoma published by the Oklahoma Geological Survey for the Fairview, Watonga, and Oklahoma City North quadrangles (Stanley and others, 2002; Fay, 2010, Stanley, 2021) and a technical review by OWRB staff geologists (**Figure 3;** orange area). The revised groundwater basin boundary is largely indistinguishable from the study area of Christenson (1983), aside from the isolated outcropping bedrock areas being conjoined into a single polygon and refined detail along the basin edges that more precisely follow topographic contours. To adhere to the lateral extent established in the 1990 final order, the 2016 model area adjacent to and south of Lake Overholster was excluded, and the area between the shifted Reach I to Reach II transition line and Canton Lake (**Figure 3**; green hashed area) was included. The groundwater basin area (excluding the area of Lake Overholster) was determined to be about 362.6 mi^2 (232,035 acres).

EPS Recommendation

The Water Right Administration Division recommends that an equal proportionate share rate between 0.50 (acre-ft/acre)/year (fifty percent scenario) and 0.63 (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 would maintain an EPS rate of 1.0 (acre-ft/acre)/year. The model-determined maximum annual yield ranged between 120,644 and 124,863 acre-feet per year, or about 2.41 to 2.50 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 32,986 acre-feet/year or about 659,750 acre-feet over the next 20 years, and current prior rights correspond to a MAY of 27,402.1 acre-feet/year or about 548,042 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

60,388.10 acre-feet per year allocated to current active regular and prior rights permits, only about seventeen (23) percent is used annually based on the mean annual groundwater use of 14,098 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 0.06 (acre-ft/acre)/year when equally distributed across the full basin area or about 0.43 (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 0.50–0.63 (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 1990 final order EPS rate of 1.0 (acre-ft/acre)/year, the life of the basin would drop to about 10 years, assuming full development. 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 II 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 120,644 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 II was calculated to be 50.1 percent for the fifty percent scenario and 48.4 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 27.3 percent for the fifty (50) percent scenario and 26.4 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 II has a developed basin area percentage of 14.2 percent.

Groundwater Quality

Christenson (1983) collected water samples from thirty-three (33) wells within the basin area to determine the concentration of common chemical constituents and selected trace constituents; all the sampling was conducted during 1980. Of the 33 samples, nine (9) were calcium bicarbonate type, nine (9) were mixed-cation bicarbonate type, nine (9) were mixed-cation mixed-anion type, nine (9) were calcium bicarbonate type, two (2) were calcium sulfate type, two (2) were calcium mixed-anion type, one (1) was sodium sulfate type, and one (1) was sodium mixed-anion 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. If no cation or anion was predominant, the type was considered mixed. Of the 33 samples collected, twenty-seven (27) had one or more chemical constituents with concentrations greater than or equal to the limits set for public supply use. Eleven (11) samples had concentrations of nitrogen that exceeded 10 milligrams per liter (mg/L), nineteen (19) samples had total dissolved solid concentrations that exceeded 500 mg/L, nine (9) samples had sulfate concentrations that exceeded 250 mg/L, one (1) samples had a chloride concentration that exceeded 250 mg/L, six (6) samples had iron concentrations that exceeded 300 micrograms per liter (ug/L), thirteen (13) samples had manganese concentrations that exceeded 50 ug/L, and two (2) samples had Selenium concentrations that exceeded 10 ug/L.

As part of the ongoing groundwater monitoring and assessment program (GMAP), the OWRB collected water samples from fourteen (14) wells across the basin area in 2015. Of the 19 samples, five (5) were calcium bicarbonate type, five (5) were mixed-cation bicarbonate type, three (3) were sodium bicarbonate type, and one (1) was calcium mixed-anion type. Inorganic nitrogen was not measured in any of the wells. Five (5) samples had sulfate concentrations that exceeded the EPS drinking water standard of 250 milligrams per liter (mg/L), one (1) sample had a chloride concentration that exceeded the EPS drinking water standard of 250 mg/L, eight (8) samples had total dissolved solid concentrations that exceeded 500 mg/L, six (6) samples had iron concentrations that exceeded 300 micrograms per liter (ug/L), and seven (7) samples had manganese concentrations that exceeded 50 ug/L. Summary statistics for selected chemical constituents are shown in **Tables 4 & 5**. High total dissolved solids, nitrogen (as nitrate), iron, and manganese are all considered water quality concerns in Reach II of the Beaver-North Canadian River Alluvium and Terrace Groundwater Basin. Although iron (Fe) and manganese (Mn) occur naturally in soils, rocks, and minerals, the relatively high concentrations of these metals in several samples imply that dissolved oxygen is being depleted from the groundwater locally. Either that or localized pumping has induced the upward migration of more mineralized groundwater from the underlying bedrock. The principal source of elevated sulfate and chloride concentrations in Oklahoma groundwater is the dissolution of halite (NaCl) and gypsum (CaSO4-2H2O) from the Permian-age bedrock units. The source of elevated nitrogen concentrations is likely anthropogenic.

Table 4. Summary statistics for groundwater-quality data for 33 samples collected by Christenson (1983)

[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	--	1,098.9	345.0	628.5	937.5	1,195.0	2,700.0	--
Temperature, ºC	--	22.6	17.5	20.0	22.1	25.0	29.3	--
pH, standard unit	--	7.0	6.5	6.9	7.0	7.2	7.8	--
Dissolved Solids, mg/L	--	734.1	230.0	409.0	568.0	881.0	2,180.0	500
Calcium, mg/L	--	103.5	41.0	68.0	88.0	120.0	260.0	--
Magnesium, mg/L	--	37.1	9.1	20.0	28.0	46.0	114.0	--
Sodium, mg/L	--	95.9	13.0	35.0	63.0	110.0	520.0	--
Potassium, mg/L	--	4.0	1.0	1.9	3.1	3.9	23.0	--
Sulfate, mg/L	--	197.0	10.0	57.0	110.0	250.0	870.0	250
Chloride, mg/L	--	72.9	9.2	28.0	40.0	79.0	400.0	250
Bicarbonate, mg/L	--	--	--	--	--	--	--	--
Fluoride, mg/L	--	0.6	0.2	0.5	0.5	0.7	1.2	2
Silica, mg/L	--	22.9	11.0	20.0	22.0	25.0	34.0	--
Alkalinity, mg/L	--	258.9	43.0	170.0	250.0	360.0	550.0	--
Inorganic Nitrogen,	--	10.4	0.1	2.5	6.7	13.0	46.0	10
Arsenic, ug/L	--	2.9	1.0	2.0	2.0	3.0	15.0	10
Boron, ug/L	--	244.5	30.0	90.0	180.0	280.0	1,100.0	--
Cadmium, ug/L	--	1.6	< 1.0	0.5	2.0	2.0	4.0	5
Chromium, ug/L	--	9.4	0.0	10.0	10.0	10.0	20.0	100
Copper, ug/L	--	30.4	0.0	5.0	11.0	24.0	430.0	1000
Iron, ug/L	--	262.7	<10.0	10.0	40.0	170.0	2,200.0	300

Parameter	Detection limit	Mean	Min	Percentile			Max	EPA Standard
				25	50	75		
Lead, ug/L	--	3.0	0.0	2.0	3.0	4.0	7.0	15
Manganese, ug/L	--	207.2	< 1.0	4.8	20.0	352.5	1,100.0	50
Selenium, ug/L	--	2.6	0.0	0.0	1.0	3.0	25.0	50
Zinc, ug/L	--	282.1	10.0	50.0	80.0	160.0	3,700.0	5000

Table 5. Summary statistics for groundwater-quality data for 14 samples collected by the Oklahoma Water Resources Board, 2015.

[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	5.0	1,196.8	529.7	698.4	954.6	1,614.2	2,616.9	--
Temperature, ºC	-5.0	19.4	17.2	18.5	19.0	20.2	23.0	--
pH, standard unit	--	6.9	6.4	6.7	6.9	7.1	7.3	--
Dissolved Solids, mg/L	10.0	732.2	313.0	408.5	559.0	946.3	1,370.0	500
Calcium, mg/L	0.5	101.4	60.4	77.3	91.3	120.0	191.0	--
Magnesium, mg/L	0.5	37.8	14.2	18.4	30.1	49.7	91.0	--
Sodium, mg/L	0.5	96.1	22.7	30.8	59.7	160.3	276.0	--
Potassium, mg/L	0.5	3.7	0.9	1.6	2.6	3.2	12.5	--
Sulfate, mg/L	10.0	182.7	39.0	81.2	136.6	261.0	454.0	250
Chloride, mg/L	10.0	77.2	15.1	21.2	58.6	108.6	281.0	250
Bicarbonate, mg/L	12.0	372.6	142.0	212.5	341.5	476.8	775.0	--
Fluoride, mg/L*	0.2	0.5	0.3	0.3	0.4	0.7	1.3	2
Silica, mg/L	0.05	25.9	22.3	24.0	25.3	27.4	34.6	--
Alkalinity, mg/L	10.0	305.4	116.0	174.3	280.0	391.0	635.0	--
Inorganic Nitrogen,	--	--	--	--	--	--	--	10
Arsenic, ug/L*	1.0	4.3	1.2	2.5	4.4	5.8	8.0	10
Boron, ug/L	20.0	198.6	45.5	60.8	154.0	262.0	586.0	--
Cadmium, ug/L	--	--	--	--	--	--	--	5
Chromium, ug/L*	1.0	23.8	10.8	16.7	20.4	30.0	45.1	100
Copper, ug/L*	1.0	9.6	1.5	1.9	4.1	7.8	45.0	1000
Iron, ug/L*	20.0	799.1	32.6	302.0	828.0	1,330.0	1,580.0	300
Lead, ug/L	0.5	--	<	<	<	0.8	1.0	15
Manganese, ug/L*	5.0	457.1	155.0	313.5	377.0	540.0	961.0	50
Selenium, ug/L	--	--	--	--	--	--	--	50
Zinc, ug/L*	5.0	0.06	0.01	0.01	0.03	0.07	0.25	5000

--, indicates not available
*, indicates statistics were based on a smaller sample population.
<, 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 II)</u>

1. Total land overlying the basin was determined to be 232,035 acres or 362.6 square miles.

2. The total amount of water in storage in Reach II in 2011 was determined to be about 1.1 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 59,942 acre-feet per year, which based on the overlying land area of the basin is equivalent to about 3.1 inches per year.

4. Total anthropogenic discharge (allocated water rights) from the basin was calculated to be about 60,388.10 acre-feet/year or about 1,207,762 acre-feet of water over the 20-year Life of the basin.

5. Values of transmissivity within the basin range from 0 to 2,050 feet squared per day. with a mean of 1,080 feet squared per day.

6. <u>Total dissolved solids, nitrogen (as nitrate), iron, and manganese are all considered water quality concerns in Reach II</u> of the Beaver-North Canadian River Alluvial and Terrace Groundwater Basin.

7. The MAY percent developed for the basin was calculated to be between 48–50 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 120,644 to 124,863 acre-feet per year, equivalent to an EPS range between 0.50 to 0.63 (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 April 1990 final order. If the Board elects to use the 1990 final order EPS rate, the life of the basin would drop to about 10 years, assuming full development. The Board subcommittee selected an EPS rate of 0.5 (acre-feet/acre)/year, equivalent to a MAY volume of 120,644 acre-feet/year.

Figure 1. Map showing saturated thickness at the end of the transient model simulation (1940–1973) in the alluvium and terrace aquifer along the Beaver-North Canadian River, Northwestern Oklahoma (Christenson, 1983).

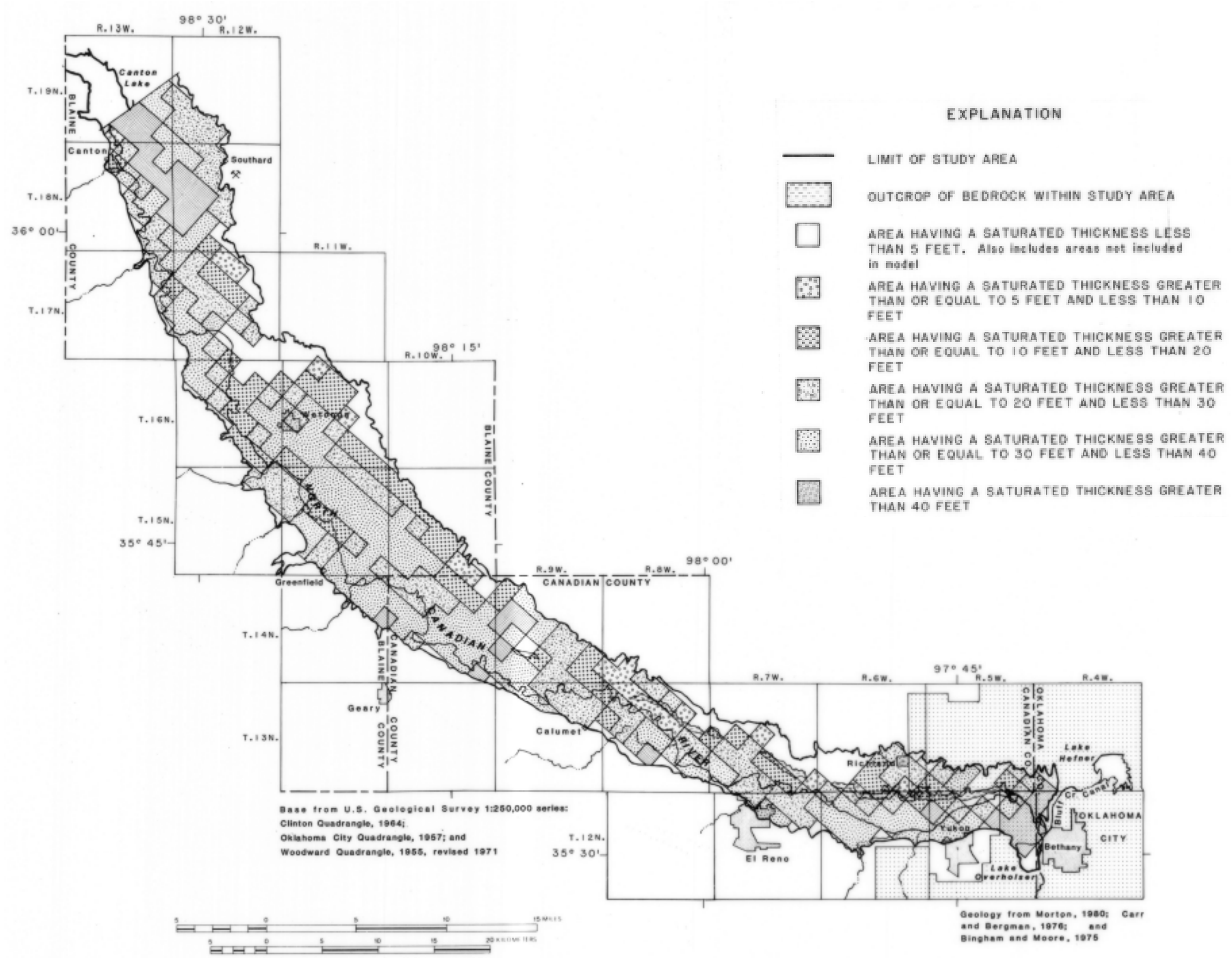


Figure 2. Map showing areas excluded from groundwater flow model simulations because of a purported lack of flow or little (less than 5 feet) or no saturation. Areas were digitized from plates 6 and 8 in Christenson (1983).

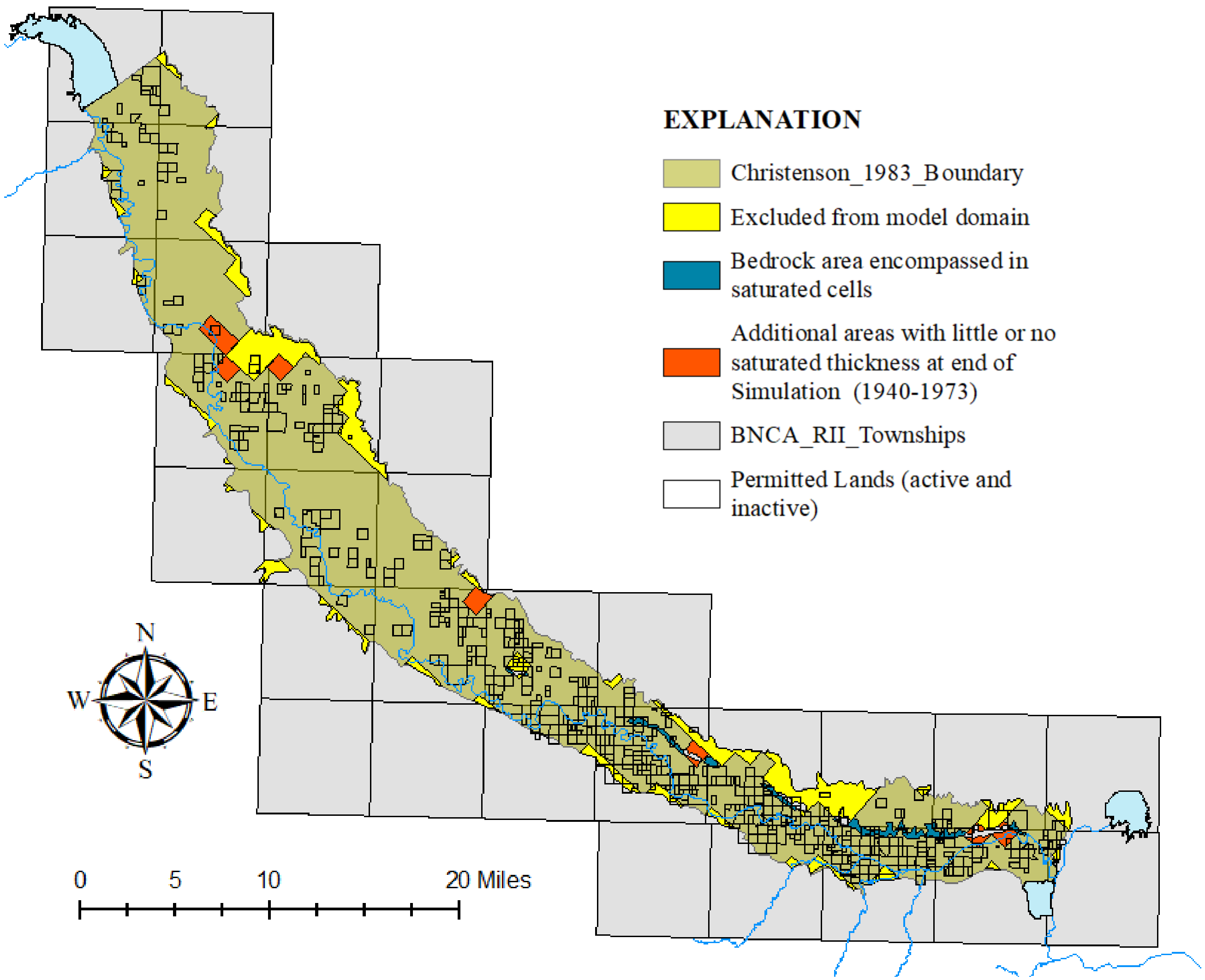
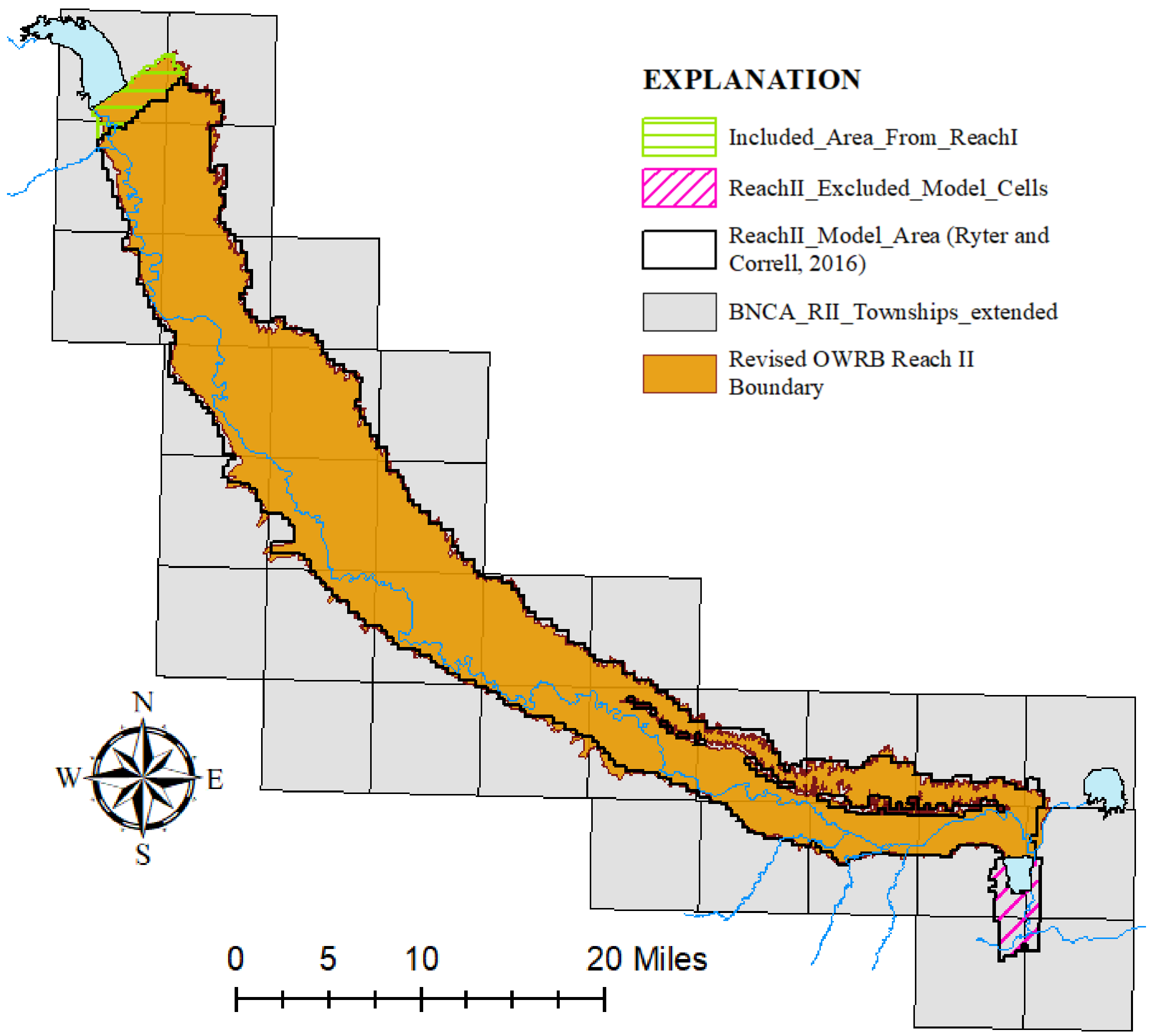


Figure 3. The revised OWRB groundwater basin area of the Beaver-North Canadian River Alluvium and Terrace Aquifer (orange region) overlain by the 2016 USGS model area (black outline). The revised groundwater basin area excluded part of the USGS Reach II model area (pink hashed area) and included part of the USGS Reach I model area (green hashed area).



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 +96 feet to -52 feet, with a mean of 1.2 feet and a standard deviation of 13.0 feet. The largest differences generally occur near the edges of the basin, where the base contours are set at a higher altitude based on more than 1,600 drillers' reports — all logs contained lithologic descriptions (most commonly "red bed") indicating the Quaternary-Permian geologic contact.

Figure S3 shows the USGS potentiometric surface (bottom) and the reevaluated OWRB potentiometric surface (top). The 160 well sites (43 in Reach II) 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 +30 to -46, with a mean of 2.6 feet and a standard deviation of 8 feet. The relative difference between the two water table surfaces is small, with large changes occurring because of contour shifting during the interpolation process based on 1,300 supplemental depth-to-water measurements from drillers' reports.

Figure S5 shows the USGS saturated thickness map (bottom) and the reevaluated OWRB saturated thickness map (top). The most apparent difference is in Canadian County along and north of the band of outcropping bedrock. In this area, most wells (85%) were drilled to depths greater than 90 feet (average of 124 feet), with depth to the base of the terrace deposits ranging from 1 to 60 feet. Wells drilled in this region of the basin generally target the underlying Duncan Sandstone because the terrace sands have little or no saturated thickness. In other areas, the saturated thickness was reduced based on changes to the base or potentiometric surface — in several areas of Blaine County cell saturated thickness in the USGS model exceeded the total thickness of local alluvium and terrace deposits based on available driller's logs. **Figure S6** shows the potentiometric surface (bottom) and base (top) maps digitized from the Christenson (1983) 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	0.73	0.73	2,609,087.88	2,609,982.35	0.034
40	0.61	0.61	4,241,684.29	4,242,064.24	0.009
50	0.61	0.61	5,312,902.67	5,313,535.85	0.012

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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.

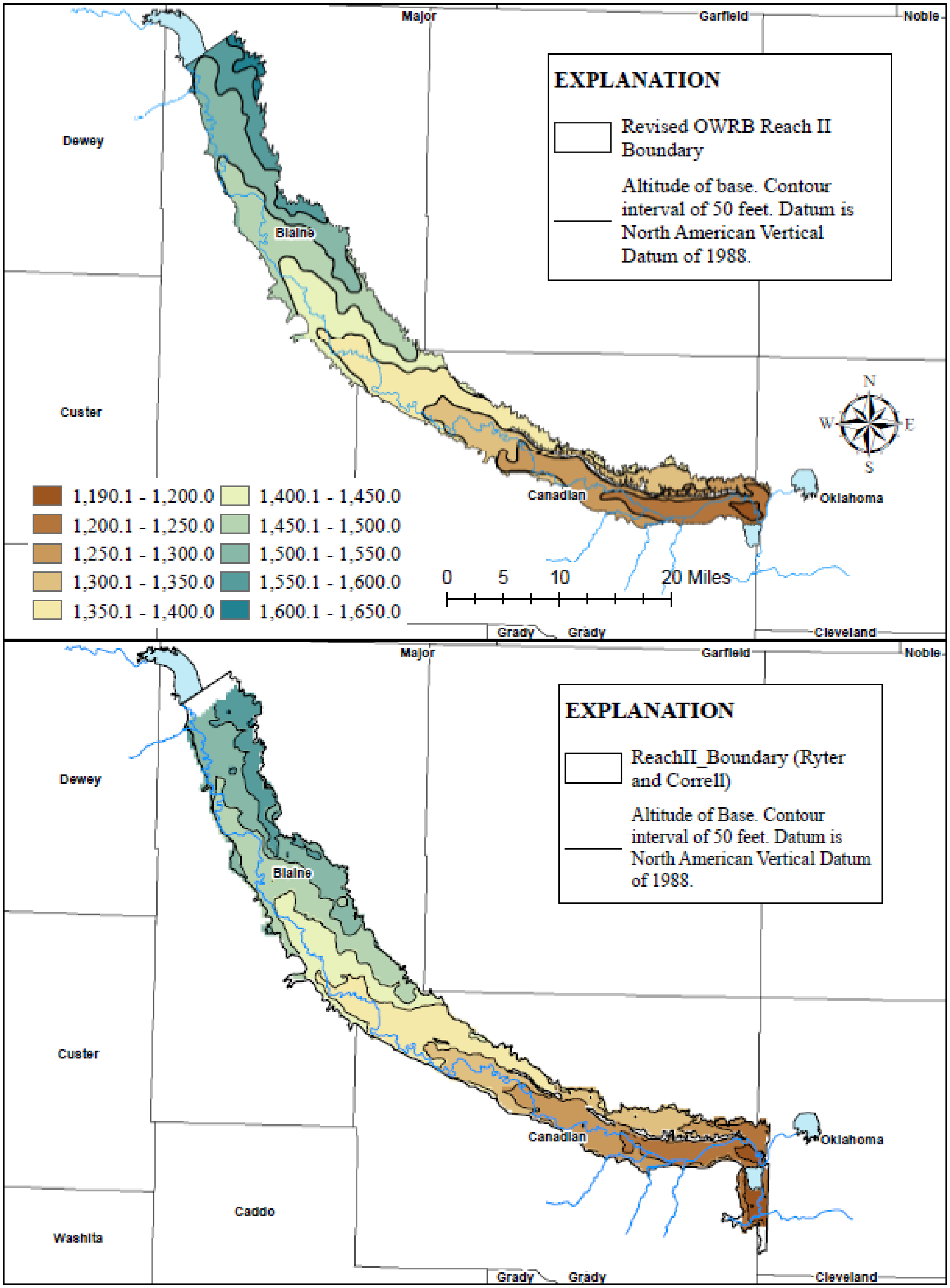

Figure S2. Residual map for the OWRB base aquifer minus the USGS aquifer base. Negative values indicate the OWRB base is below the USGS base and positive values indicate the OWRB base is above the USGS base. The average difference between the two base maps is 1.2 feet.

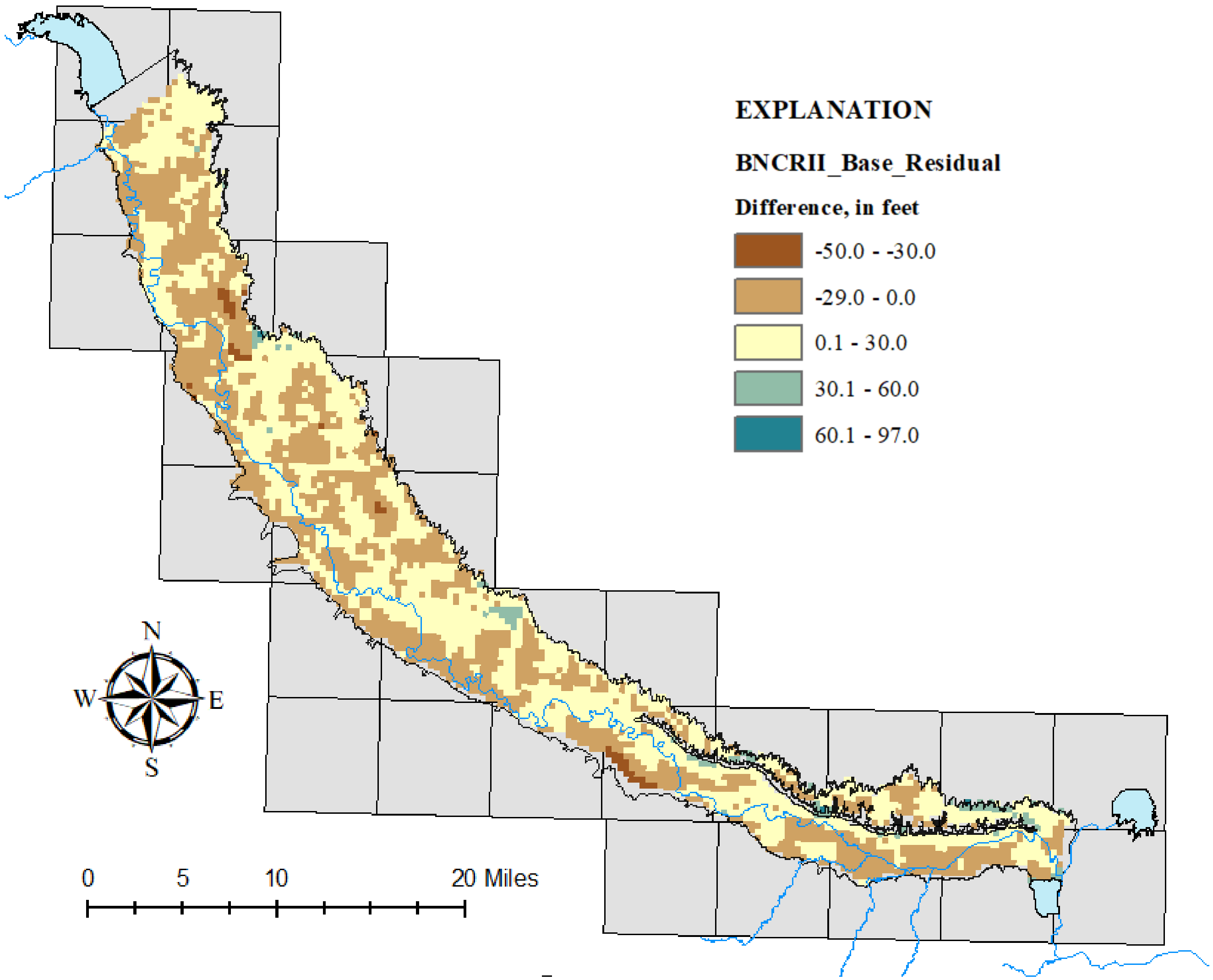

Figure S3. The USGS potentiometric surface map (bottom) and reevaluated OWRB potentiometric surface map (top). Both maps used the same altitude intervals which is only shown in the top figure.

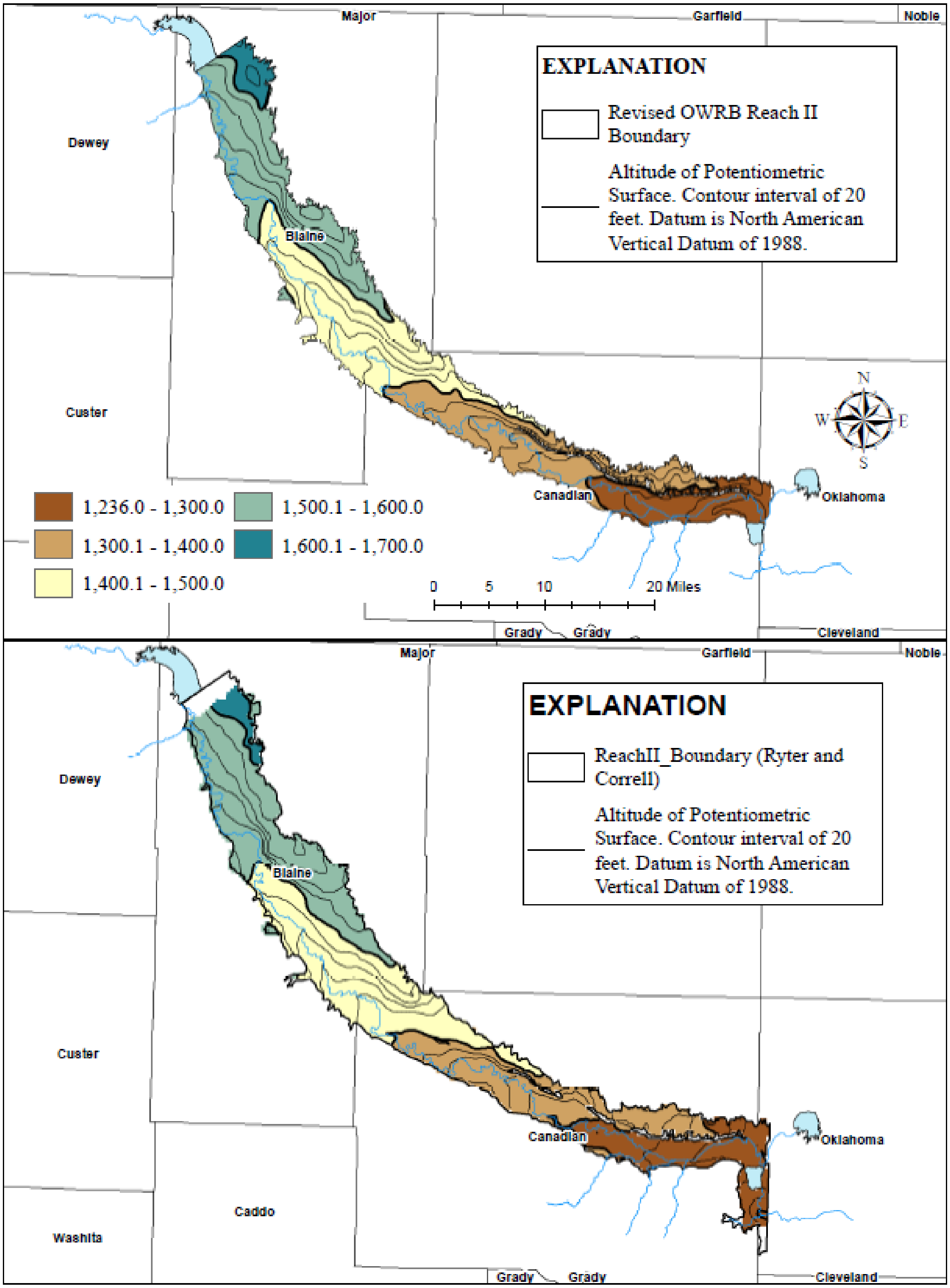

Figure S4. Residual map for the OWRB potentiometric surface minus the USGS potentiometric surface. Negative values indicate the OWRB potentiometric surface is below the USGS POT, and positive values indicate the OWRB potentiometric surface is above the USGS POT. The average difference between the two base maps is 2.6 feet.

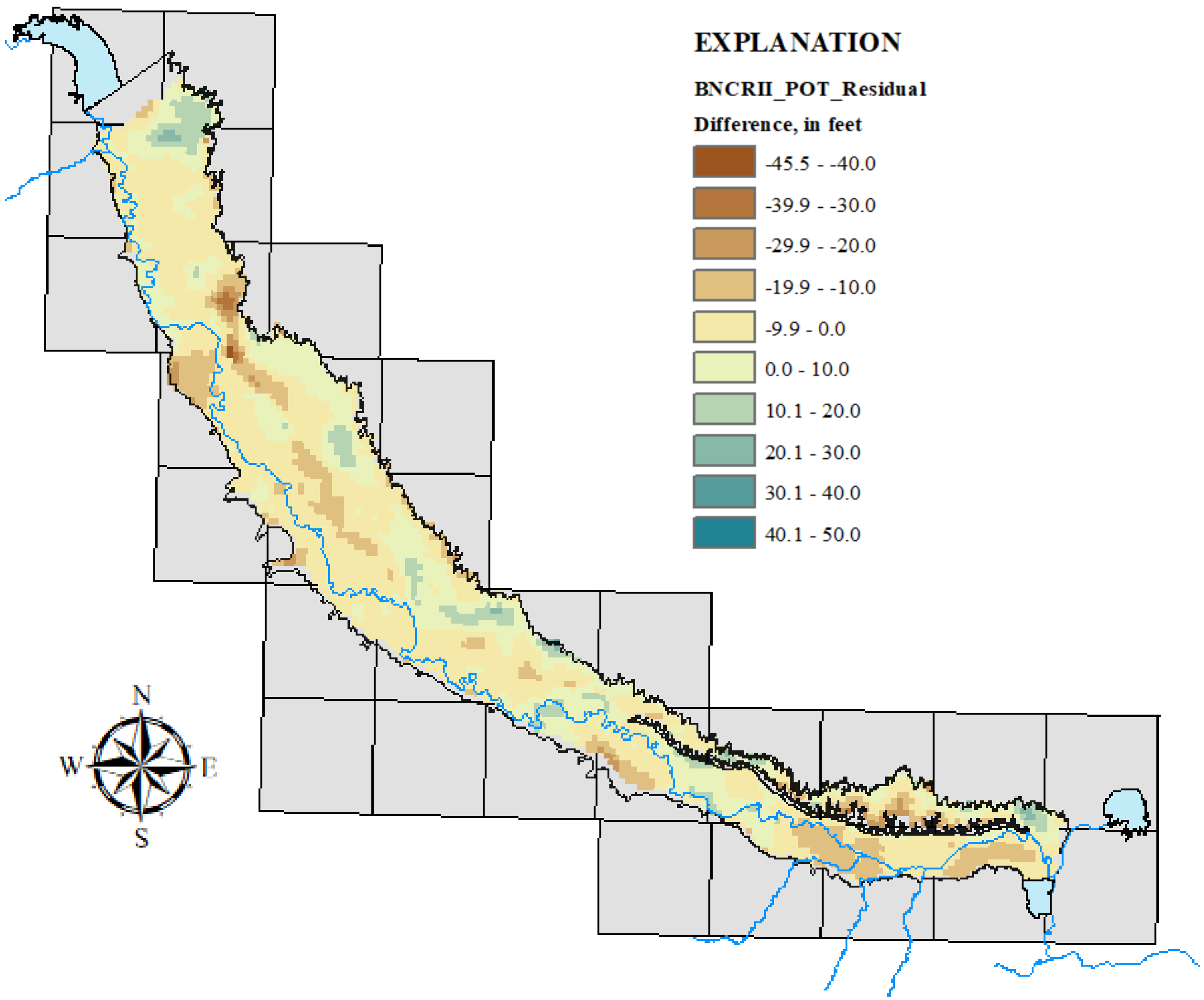

Figure S5. The OWRB saturated thickness map (top) and 2016 USGS saturated thickness map (bottom).

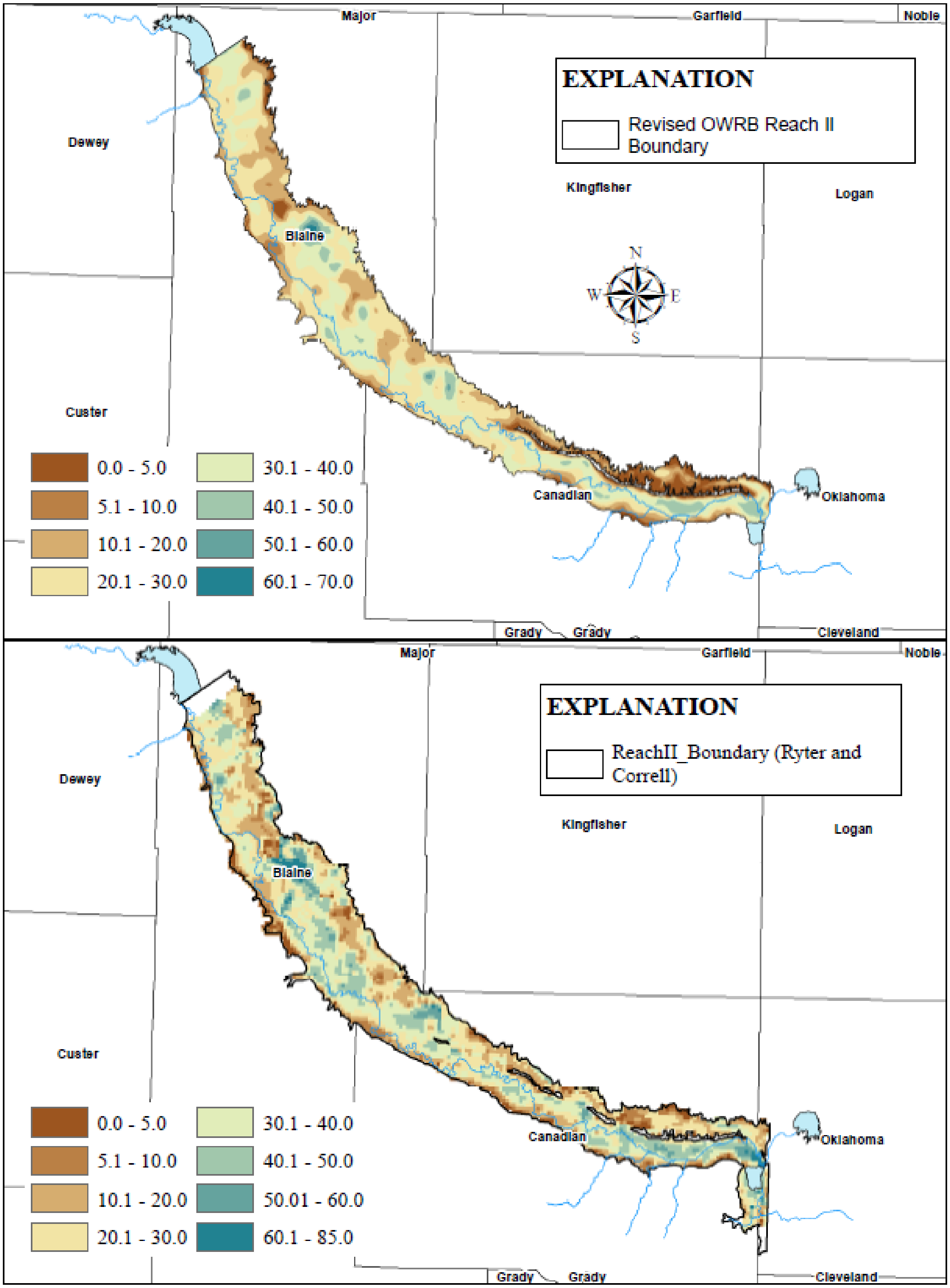

Figure S6. The Christenson (1983) base map (top) and potentiometric surface map (bottom). The maps use the same altitude intervals as the USGS and OWRB maps in Figures S1 and S3.