Chapter 6

Powder/Tongue/Northeast River Basins (NERB) hydrogeology and groundwater resources

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Wyoming's groundwater resources occur in both unconsolidated deposits and bedrock formations. In the NERB, the Tertiary aquifer system is the most frequently used hydrogeologic unit (Thamke and others, 2014; figs. 8-1 through 8-7). In addition, more than 15 other bedrock aquifers and their stratigraphic equivalents (fig. 7-2) provide variable amounts of useable groundwater. These aquifers range in geologic age from Paleozoic to Quaternary.

Generally, aquifers are defined as geological units that store and transport useable amounts of groundwater while less permeable, confining units impede groundwater flow (sec. 5.1.1). In practice, the distinction between aquifers and confining units is not as clear. A geologic unit that has been classified as confining at one location may act as an aquifer at another. Virtually all geologic units in the NERB, including confining units, are capable of yielding at least small quantities of groundwater. For example, the Lebo Shale member of the Fort Union Formation is identified as an aquifer in areas where it is locally productive but is considered a confining unit elsewhere (Thamke, 2014). In addition, numerous springs discharge water from this unit at the surface (pl. 3). Permeability can vary widely within an individual geologic unit depending on its lithology and the geologic structure present. Carbonate aquifers, such as the Madison Limestone, commonly exhibit the highest yields in areas where secondary permeability (e.g., solution openings, bedding plane partings, and fractures) has developed. The great differences in permeability between and within geologic units account, in part, for the observed variation in the available quantity and quality of a basin's groundwater resources.

A primary purpose of this study is to evaluate the groundwater resource of the NERB primarily through the following tasks (chap. 1):

- Estimate the quantity of water in the aquifers
- Describe the aquifer recharge areas
- Estimate aquifer recharge rates
- Estimate the "safe yield" potential for the aquifers

The complex geology of the NERB, as discussed in chapter 4, does not permit the basin-wide application of general assumptions regarding aquifer geometry, saturated thickness, and hydraulic properties commonly used to estimate total and producible groundwater resources. The data required for a basin-wide, aquifer-specific assessment of all groundwater resources are not available currently. Groundwater resources evaluated in this study rely on estimates (Taboga and Stafford, 2016) of the percentage of precipitation in areas where aquifer units crop out that will ultimately reach the subsurface as recharge (figs. 6-1 through 6-7) and the formulation of a basin-wide water balance (chap. 8). The technical and conceptual issues concerning recharge are discussed in section 5.1.3.

Additionally, geoscience has evolved beyond the concept of safe yield since it was first introduced by Lee (1915). Instead, many water resource professionals now consider sustainable development of groundwater. The recharge volumes estimated in this chapter provide a first step to evaluating sustained yields for the basin's hydrologic units. The historical development of the safe yield concept and its technical context is discussed in section 5.1.4.

6.1 HYDROSTRATIGRAPHY AND RECHARGE TO AQUIFER OUTCROPS

To evaluate recharge, specific aquifers and groups of aquifers must be distinguished (figs. 6-1 through 6-7). Previous studies (sec. 2.1) have grouped the NERB's hydrogeologic units into various combinations of aquifers, aquifer systems, and confining units (Lewis and Hotchkiss, 1981; Thamke and others, 2014). The hydrostratigraphy developed for this study is based on previous regional assessments and is summarized in plate 2, in hydrostratigraphic charts (figs. 7-2 and 7-8), and in chapter 7. The hydrostratigraphic charts in figures 7-2 and 7-8 detail the hydrogeologic nomenclature used in previous studies, including the aquifer classification system from the Statewide Framework Water Plan (WWC Engineering and others, 2007). Appendix A describes the geologic units used to develop the surface hydrogeology map (pl. 2).

Section 5.2 discusses how the map units of Love and Christiansen (1985), compiled into a Geographic Information Systems (GIS) database by the U.S. Geological Survey (USGS) and Wyoming State Geological Survey (WSGS), were used to develop plate 2. Love and Christiansen (1985), however, were unable to distinguish all stratigraphic units present due to the sheer size of the dataset, cartographic limitations, and stratigraphic complexity. Thus, not all geologic units are differentiated on their map. Further, the large number of hydrostratigraphic units in the NERB (chap. 7, pl. 2) make it impractical to calculate recharge for each unit. Instead, the WSGS aggregated the numerous stratigraphic units by geologic age and hydrostratigraphy and then generated GIS shapefiles to calculate recharge volumes and rates. WSGS generally followed the classifications used by the USGS (Thamke and others, 2014; Long and others, 2014):

- Quaternary aquifers (fig. 6-1)
- Lower Tertiary aquifer system (fig. 6-2)
- High Plains aquifer system (fig. 6-3)
- Upper Cretaceous aquifer system (fig. 6-4)
- Other Cretaceous aquifers (fig. 6-5)
- Paleozoic aquifers (fig. 6-6)
- Precambrian units (fig. 6-7)

6.2 AVERAGE ANNUAL RECHARGE

Because of evapotranspiration and natural discharge to streams, springs, lakes, and wetlands, only a fraction of the groundwater stored in the NERB can be withdrawn for beneficial use. Under natural conditions, a state of dynamic equilibrium exists where natural discharges to surface waters and evapotranspiration are balanced by recharge. In effect, this balance means that higher rates of recharge result in higher levels of natural discharge. Withdrawals from wells and springs remove groundwater from aquifer storage and diminish natural discharges, most notably, streamflows. Thus, without careful management, riparian ecosystems will collapse and surface water rights holders will not receive their full appropriation, because over time, groundwater discharges to springs, streams, and wetlands will be depleted. This risk has long been recognized by Wyoming's agricultural community, water resource professionals, and legislators. The connection between surface water and groundwater resources has been incorporated into Wyoming's water law and some of Wyoming's interstate water compacts, such as the Amended Bear River Compact of 1978 and 2001 Modified North Platte River Decree. Barlow and Leake (2012) provide an explanation of the connection of groundwater and surface water (https://pubs.er.usgs.gov/publication/cir1376).

To evaluate recharge on a regional scale, this study combines estimated average annual recharge data from the WSGS statewide recharge study (Taboga and Stafford, 2016) with maps illustrating where important hydrogeologic units crop out in the NERB (pl. 2; figs. 6-1 through 6-7).

Valuable baseline date is generated by examining periodic water levels and average annual recharge balanced with best estimates of annual discharge (both natural and by pumping). These data help to establish benchmarks for sustained yield, namely the volume of water that can be artificially discharged without unacceptably depleting aquifer storage or natural discharges. While aquifer-specific recharge can be reasonably estimated, aquifer-specific discharges are difficult to constrain. Estimates of annual groundwater withdrawals and consumptive uses from the previous NERB water plans (HKM and others, 2002a, b; RESPEC, 2019a, b) and the Statewide Framework Water Plan (WWC Engineering and others, 2007) are discussed in chapter 8.

Estimated average annual recharge (fig. 5-2) in the Wyoming portion of the NERB ranges from less than one inch per year in the basin interior to more than 37 inches per year in the Bighorn Mountains (Taboga and Stafford, 2016). Mountains and foothills receive more recharge than basin lowlands due to favorable environmental attributes present in highland zones:

- Greater amounts of precipitation and more persistent snow pack (fig. 3-3)
- Vegetation that favors the accumulation of snowpack, such as trees and brush
- Thin, permeable mountain soils
- Lower rates of evapotranspiration
- Permeable exposures of upturned and weathered bedrock
- The presence of structural features that enhance recharge (e.g., faults, fractures, joints, and fault/fracture-controlled surface drainages)

Figure 6-8 shows how recharge efficiency, defined as a percentage of average annual precipitation (R/P), varies throughout the Wyoming portion of the NERB and suggests what environmental factors exert control on recharge. Recharge is most efficient in and around the Bighorn Mountains and Black Hills, and slightly higher in portions of Sheridan, Campbell, and Niobrara counties. The dataset for figure 6-8 was generated by dividing 4,000-m grid cells and assigning values for average annual aquifer recharge (fig. 5-2) and average annual precipitation (fig. 3-3) to each cell.

Average annual recharge estimates (fig. 5-2) were obtained from a WSGS model (Taboga and Stafford, 2016) that uses publicly available precipitation, land slope, and soil permeability data to calculate recharge. Total average annual precipitation has been estimated (PRISM, 2013) as 18,784,902 acre-feet for the larger NERB shown in figure 3-3 and 18,158,416 acre-feet for

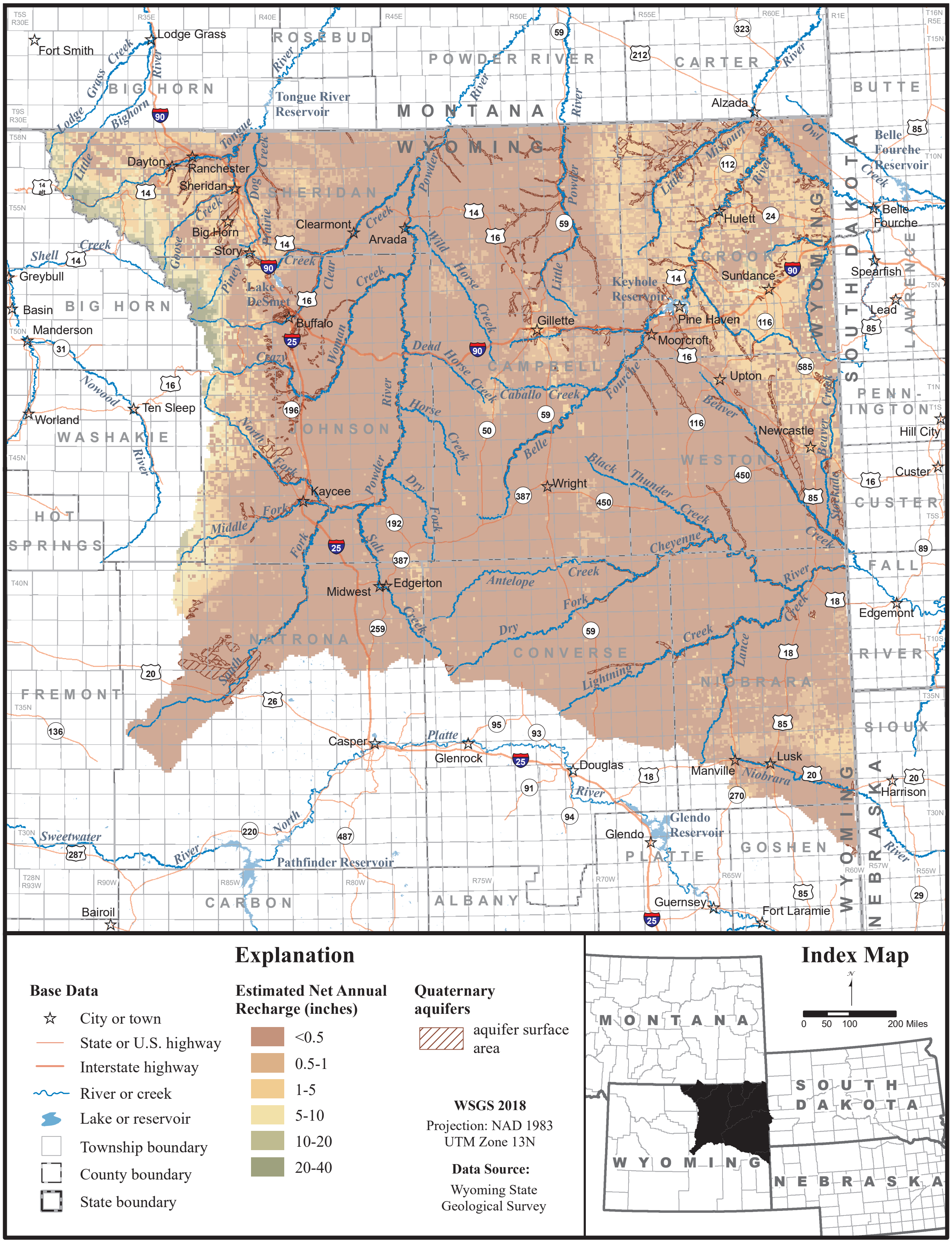

Figure 6-1. Estimated net annual aquifer recharge—surface Quaternary aquifer, NERB, Wyoming.

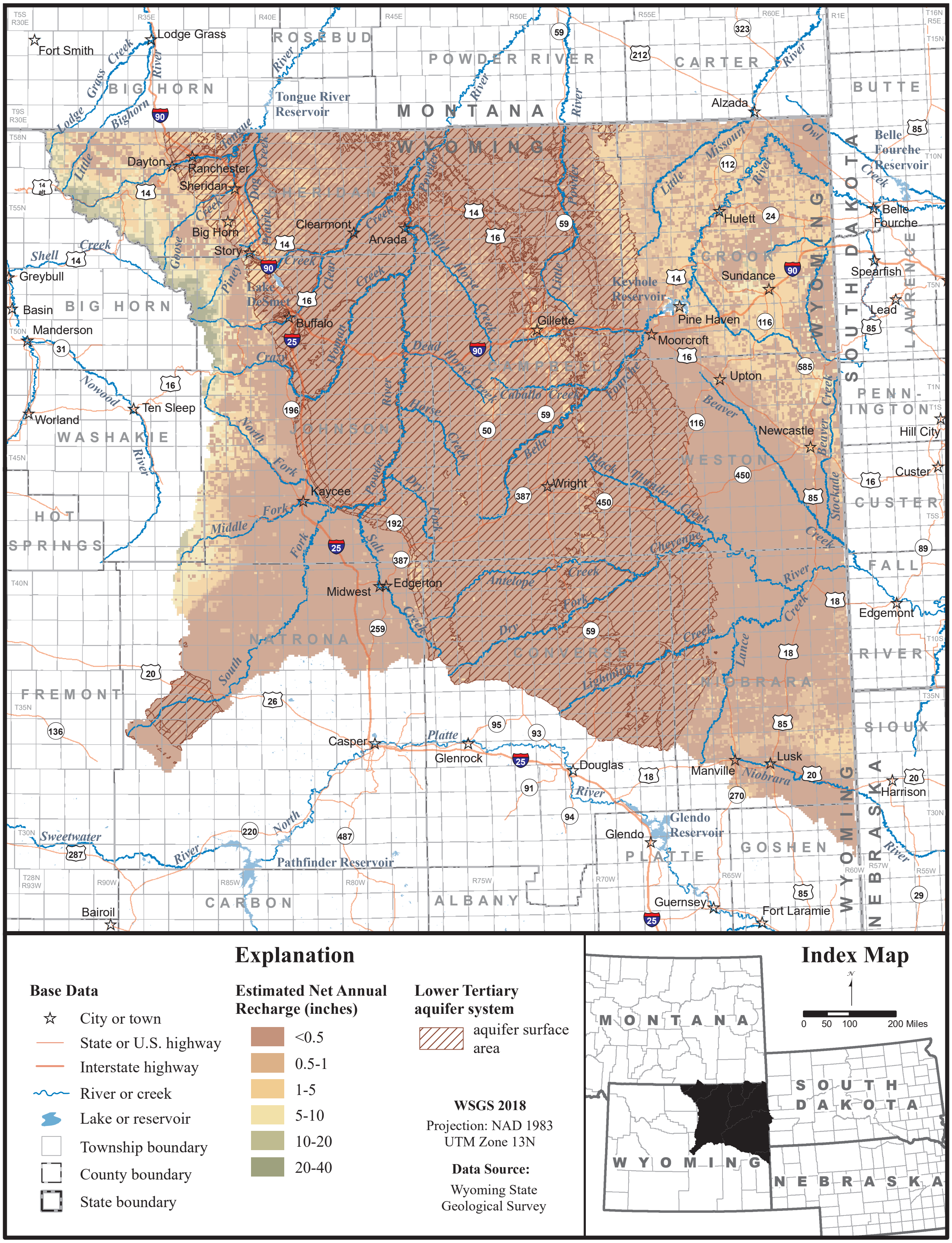

Figure 6-2. Estimated net annual aquifer recharge—surface Lower Tertiary aquifer system, NERB, Wyoming.

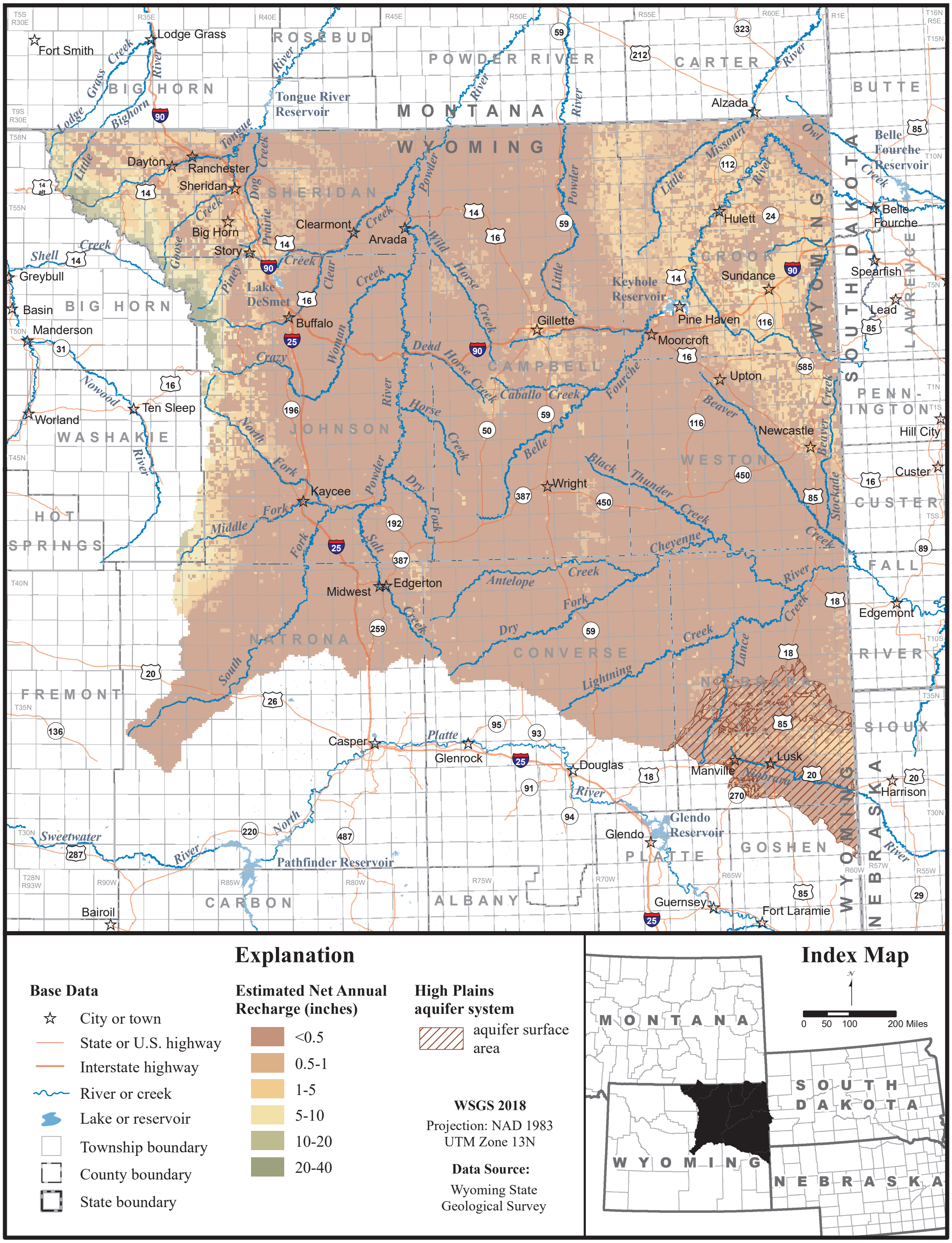

Figure 6-3. Estimated net annual aquifer recharge—surface High Plains aquifer system, NERB, Wyoming.

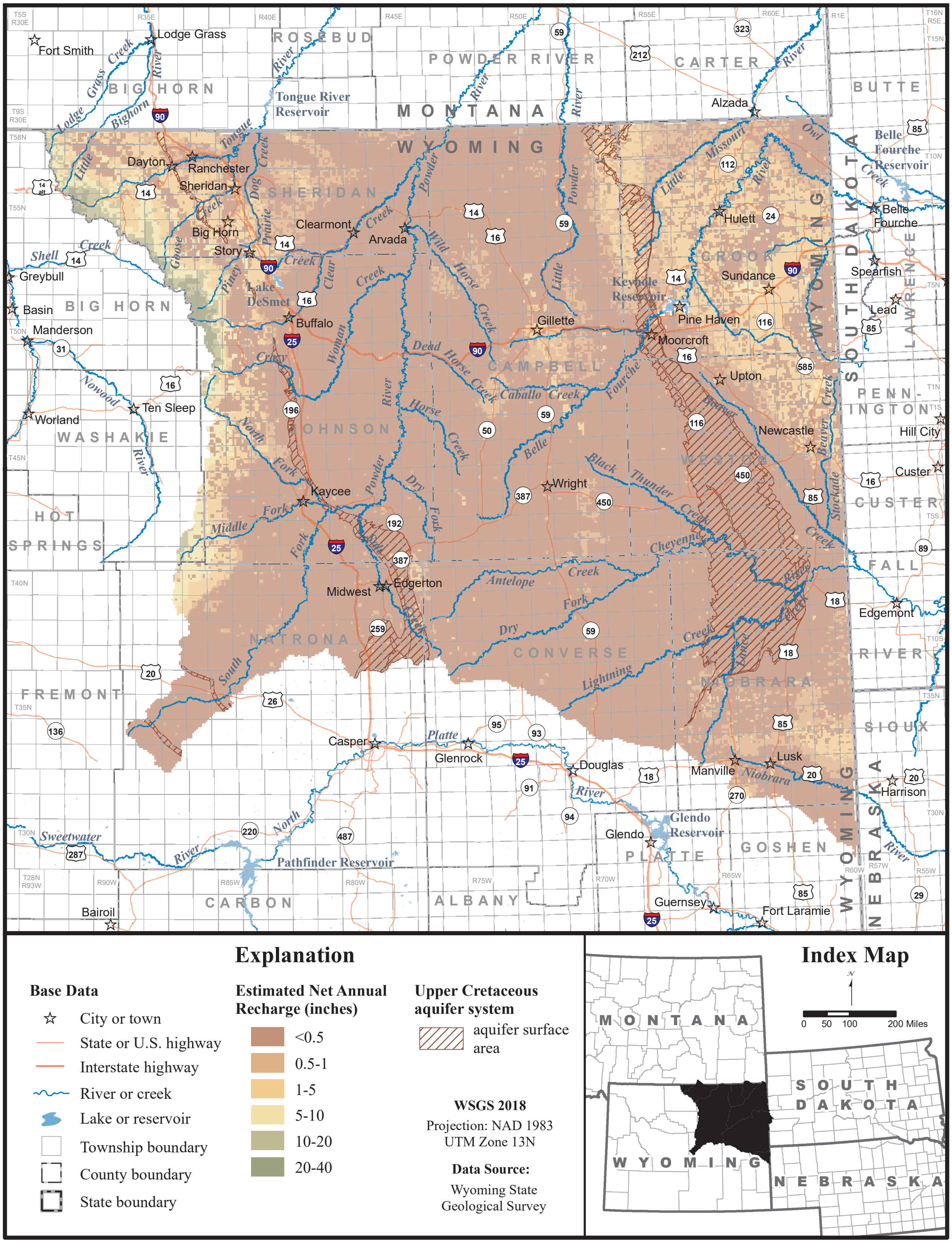

Figure 6-4. Estimated net annual aquifer recharge—surface Upper Cretaceous aquifer system, NERB, Wyoming.

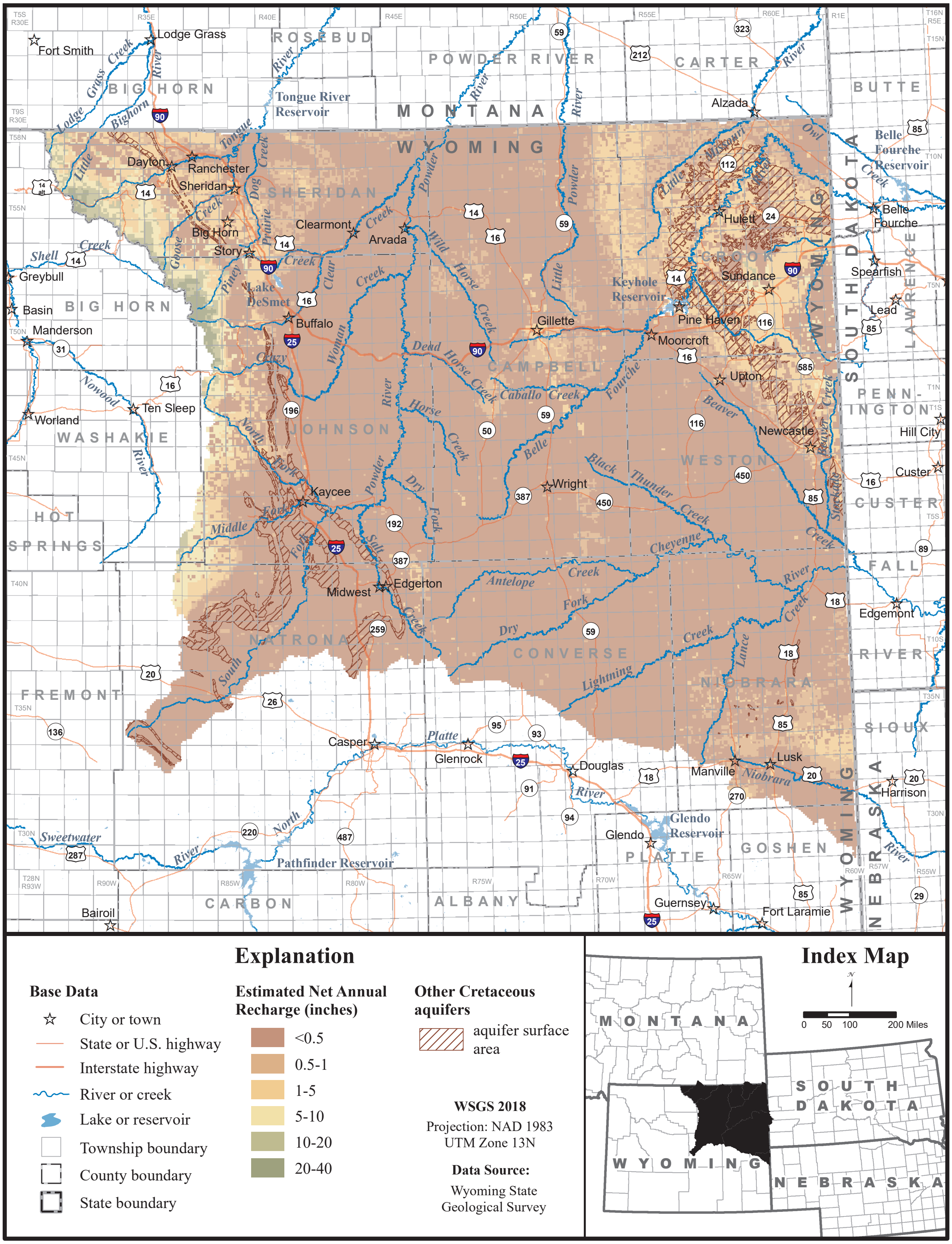

Figure 6-5. Estimated net annual aquifer recharge—surface Other Cretaceous aquifers, NERB, Wyoming.

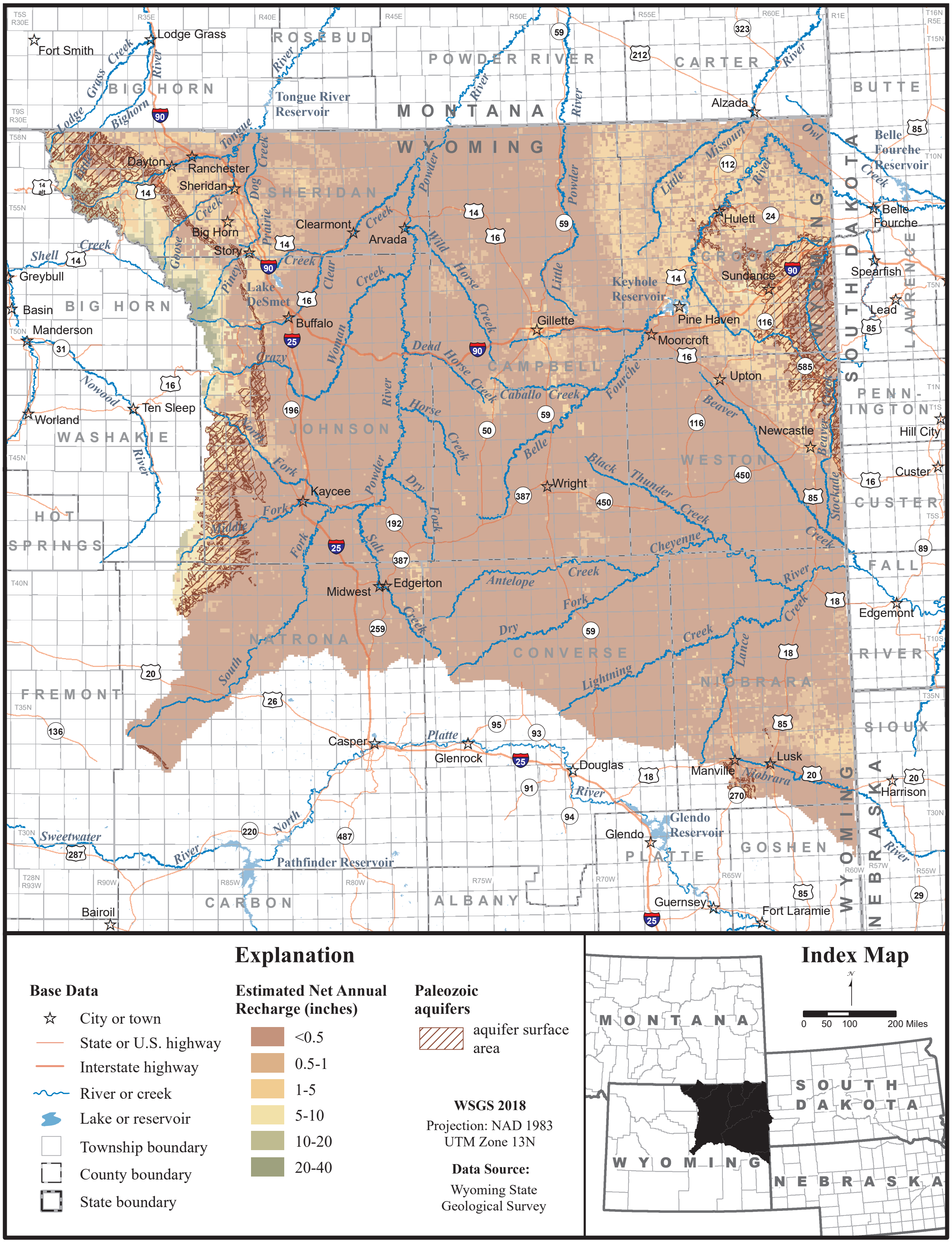

Figure 6-6. Estimated net annual aquifer recharge—surface Paleozoic aquifer, NERB, Wyoming.

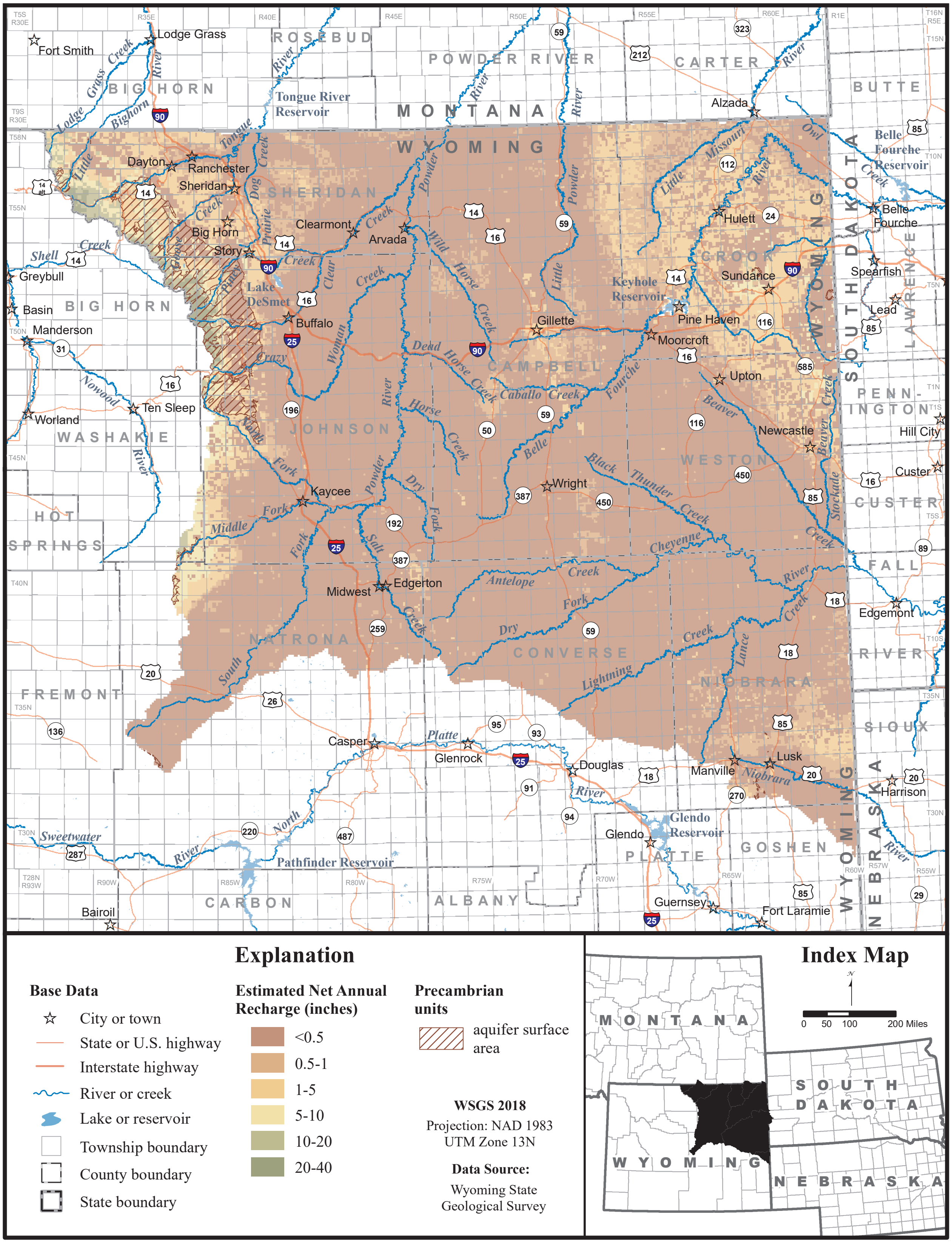

Figure 6-7. Estimated net annual aquifer recharge—surface Precambrian units, NERB, Wyoming.

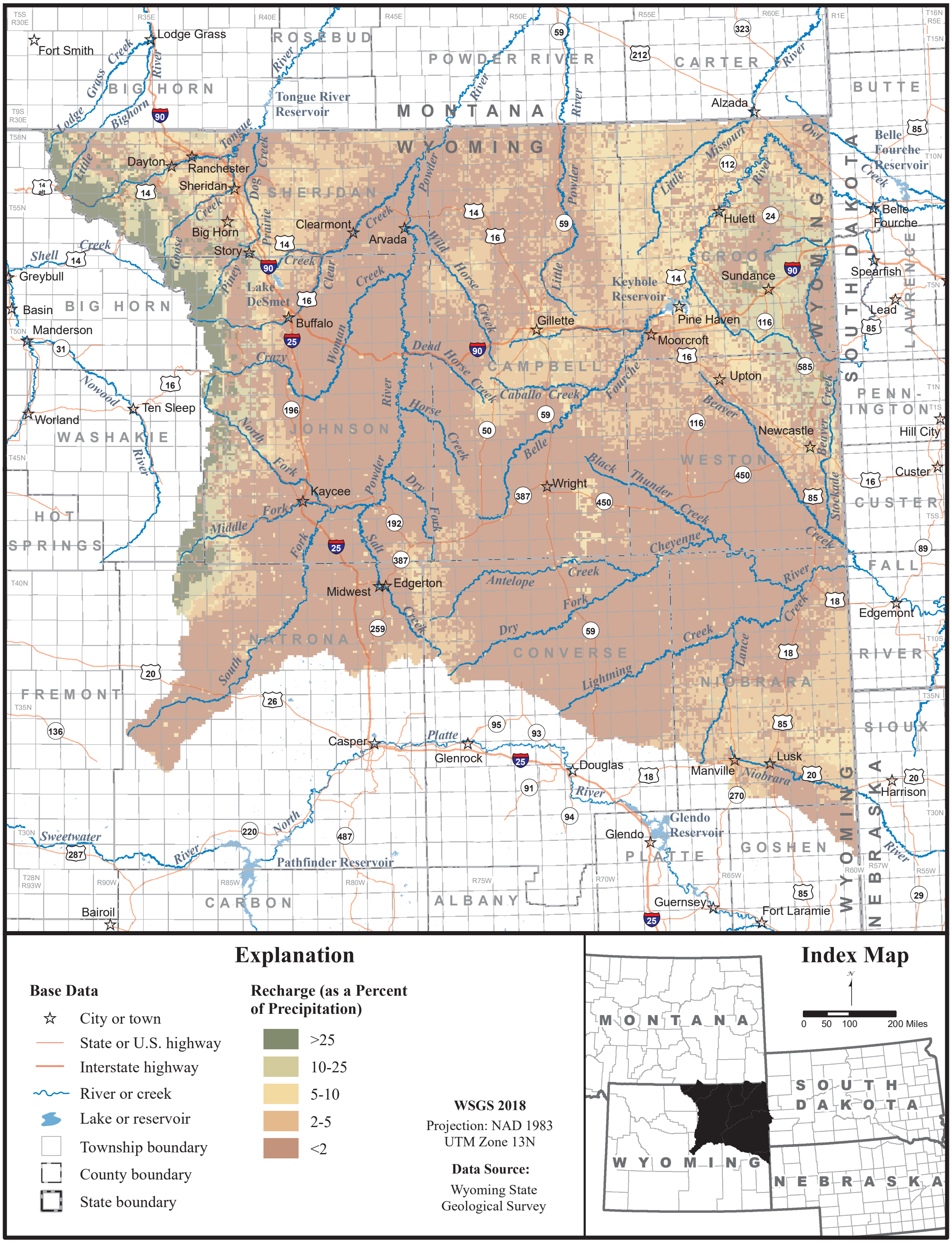

Figure 6-8. Aquifer recharge as percentage of precipitation using 1981–2010 precipitation normals, NERB, Wyoming.

the Wyoming portion exclusively (table 8-2a). Although this approach does not fully consider all factors that affect recharge, initial infiltration and precipitation levels are generally the most important factors on a regional scale. Consideration of the other factors listed above and in section 5.1.3.1 should confirm the general pattern of recharge efficiency displayed in figure 6-8. However, as discussed previously (secs. 5.1.3.1 and 5.4), local recharge rates may be dominated by site-specific hydrogeologic conditions (e.g., solution-enhanced fracture permeability, permeable outcrops such as scoria). Lastly, the WSGS Recharge Model (Taboga and Stafford, 2016) indicated some areas in the basin interior receive no recharge (figure 5-2).

Table 6-1 shows the percentage of surface area by specified range of recharge efficiency, as R/P and as determined via GIS analysis, for each of the seven classified aquifer recharge zones (pl. 2, figs. 6-1 through 6-7).

Table 6-1 shows that Quaternary, Tertiary, and Upper Cretaceous aquifers receive recharge at efficiencies of less than 5 percent of precipitation. In contrast, Paleozoic, Precambrian, and Lower Cretaceous aquifers receive recharge at efficiencies of 5 percent or greater, likely due to these aquifers being exposed in upland areas. The consistently low recharge efficiencies calculated for Upper Cretaceous, Tertiary, and Quaternary aquifer zones likely reflect the greater aridity (fig. 3-3) within the interior of the NERB.

Recharge volumes for the established aquifer recharge areas were calculated with the following, general equation:

Average annual recharge volume (acre-feet)= Aquifer recharge area (acres) × Average annual recharge (feet)

Surface exposures assigned to aquifer groups in the recharge calculations (figs. 6-1 through 6-7) were determined from the hydrogeologic map (pl. 2) developed for this study. Average annual rates of recharge throughout the NERB (mapped in 800-m cells) are shown in figure 5-2. Recharge rates were grouped into the five ranges to make figure 6-8 more readable and to mitigate uncertainties associated with the recharge calculations. Recharge rates for the aquifer recharge zones, mapped as polygons, were converted from inches to feet, and the average annual recharge volumes (in acre-feet) were calculated using the equation above.

Recharge calculations contained in this report do not incorporate confining unit exposures (pl. 2). As noted in section 5.2, undifferentiated geologic units were included in the established aquifer recharge areas of the same age. Recharge calculations that exclude confining-unit exposures provide a more conservative estimate of available groundwater resources. Furthermore, this evaluation disregarded leakage from adjacent confining.

Table 6-1. Aquifer recharge efficiencies, in percentages, for aquifers grouped by geologic age.

Recharge efficiency as annual recharge / annual precipitation, (in percentage)	0-2%	2%-5%	5%-10%	10%-25%	>25%
Quaternary	65.14%	19.30%	11.32%	3.98%	0.26%
Lower Tertiary System	74.58%	19.36%	5.31%	0.73%	0.03%
High Plains System	32.99%	54.08%	11.59%	1.34%	0.00%
Upper Cretaceous System	80.33%	13.21%	6.10%	0.36%	0.00%
Other Cretaceous Aquifers	32.67%	12.80%	18.16%	25.05%	11.32%
Paleozoic Aquifers	41.06%	4.02%	7.39%	33.93%	13.60%
Precambrian Units	30.77%	5.58%	6.68%	19.66%	37.32%

Table 6-2 summarizes calculated recharge for the NERB over the ranges of average annual recharge mapped on figure 5-2 alongside the aquifer recharge zones displayed in figures 6-1 through 6-7. A "best total" amount for each range of recharge over the exposed area of each aquifer group is provided in tables 6-2 and 6-3, and is based on the recharge area for each whole inch of recharge in the database compiled for this study. The "best total" is calculated directly from the detailed cell-by-cell recharge data and the corresponding surface area.

Table 6-3 summarizes calculated average annual recharge statistics from the more detailed calculations provided in table 6-2. Additionally, table 6-3 provides a "best total" average recharge depth delivered over the entire surface area of each aquifer recharge zone. An analysis of average recharge depths shows that high elevation Precambrian aquifers receive 0.73 ft (8.8 in) of recharge compared to about 0.95 and 0.6 in, respectively, in Quaternary and Tertiary (lower Tertiary system and High Plains aquifer combined). The Upper Cretaceous aquifer system, which

Table 6-2. NERB average annual recharge calculations (Taboga and Stafford, 2016; PRISM, 2013).

ERA	Range of average recharge per year		Outcrop area receiving recharge	Average annual recharge
	(inches)	(feet)	(acres)	Best total (acre-feet)
Quaternary aquifers	0.0–0.5	0.00–0.04	103,431	3,393
	0.5–1.0	0.04–0.08	72,467	4,755
	1.0–5.0	0.08–0.42	69,267	9,695
	5.0–10.0	0.42–0.83	3,858	1,837
	10.0–20.0	0.83–1.67	0.00	0.00
	20.0–40.0	1.67–3.33	0.00	0.00
TOTAL			**249,022**	**19,680**

ERA	Range of average recharge per year		Outcrop area receiving recharge	Average annual recharge
	(inches)	(feet)	(acres)	Best total (acre-feet)
Lower Tertiary aquifer system	0.0–0.5	0.00–0.04	1,700,210	55,781
	0.5–1.0	0.04–0.08	525,640	34,491
	1.0–5.0	0.08–0.42	238,174	29,292
	5.0–10.0	0.42–0.83	2,890	1,543
	10.0–20.0	0.83–1.67	0	0
	20.0–40.0	1.67–3.33	0	0
TOTAL			**2,466,913**	**121,106**

Table 6-2. continued

ERA	Range of average recharge per year (inches)	(feet)	Outcrop area receiving recharge (acres)	Average annual recharge Best total (acre-feet)
High Plains aquifer system	0.0–0.5	0.00–0.04	362,483	11,893
	0.5–1.0	0.04–0.08	153,856	10,096
	1.0–5.0	0.08–0.42	60,609	6,686
	5.0–10.0	0.42–0.83	0	0
	10.0–20.0	0.83–1.67	0	0
	20.0–40.0	1.67–3.33	0	0
TOTAL			**576,948**	**28,674**

ERA	Range of average recharge per year (inches)	(feet)	Outcrop area receiving recharge (acres)	Average annual recharge Best total (acre-feet)
Upper Cretaceous aquifer system	0.0–0.5	0.00–0.04	253,523	8,318
	0.5–1.0	0.04–0.08	72,275	4,742
	1.0–5.0	0.08–0.42	47,840	5,391
	5.0–10.0	0.42–0.83	0	0
	10.0–20.0	0.83–1.67	0	0
	20.0–40.0	1.67–3.33	0	0
TOTAL			**373,638**	**18,451**

Table 6-2. continued

ERA	Range of average recharge per year (inches)	(feet)	Outcrop area receiving recharge (acres)	Average annual recharge Best Total (acre-feet)
Other Cretaceous aquifers	0.0–0.5	0.00–0.04	37,903	1,244
	0.5–1.0	0.04–0.08	53,465	3,508
	1.0–5.0	0.08–0.42	265,172	45,054
	5.0–10.0	0.42–0.83	9,269	4,652
	10.0–20.0	0.83–1.67	0	0
	20.0–40.0	1.67–3.33	0	0
TOTAL			**365,809**	**54,458**

ERA	Range of average recharge per year (inches)	(feet)	Outcrop area receiving recharge (acres)	Average annual recharge Best total (acre-feet)
Paleozoic aquifers	0.0–0.5	0.00–0.04	28,997	951
	0.5–1.0	0.04–0.08	27,401	1,798
	1.0–5.0	0.08–0.42	331,241	80,608
	5.0–10.0	0.42–0.83	104,264	56,793
	10.0–20.0	0.83–1.67	30,283	36,158
	20.0–40.0	1.67–3.33	8,204	14,753
TOTAL			**530,390**	**191,062**

NERB TOTAL ***(recharge for sedimentary aquifers)***	**4,562,721**	**433,431**

Table 6-2. continued

ERA	Range of average recharge per year (inches)	(feet)	Outcrop area receiving recharge (acres)	Average annual recharge Best total (acre-feet)
Precambrian units	0.0 0.5	0.00 0.04	14,939	490
	0.5 1.0	0.04 0.08	16,240	1,066
	1.0 5.0	0.08 0.42	99,473	24,272
	5.0 10.0	0.42 0.83	96,752	59,535
	10.0 20.0	0.83 1.67	57,973.47	69,721.47
	20.0 40.0	1.67 3.33	40812.75	84,229.63
TOTAL			**326,190**	**239,313**

is exposed in highland areas located primarily in northern and central parts of the basin (pl. 2), receives 0.05 ft (~0.59 in) of recharge. Infiltration through Paleozoic and volcanic strata provides about 64 percent of the basin's recharge.

In the Wyoming part of the NERB, the best estimate of total recharge is 672,744 acre-feet, or about 4 percent of total precipitation.

6.3 SUMMARY

- Recharge is ultimately controlled by precipitation. Total average annual precipitation for the entire NERB (fig. 3-2) has been estimated as 18,784,902 acre-feet, with 18,158,416 acre-feet being the estimated Wyoming portion (table 8-2a).
- Recharge controlled by precipitation and soil/vegetation combinations in the Wyoming portion of the NERB ranges up to 37 in (Taboga and Stafford, 2016), with the lowest values occurring in the interior basins and the highest values in the upland drainages of the surrounding mountain ranges.
- Other factors controlling recharge may dominate locally (e.g., solution enhanced fractures). However, consideration of these factors should confirm the overall pattern of recharge and recharge efficiency.
- Recharge from precipitation to flat-lying Tertiary and Quaternary aquifers in the interior basin is generally less efficient than recharge to the exposed Paleozoic aquifers and Precambrian units in the mountainous areas. Recharge in the NERB is most efficient in higher elevation, Paleozoic terrains.
- Estimates of average annual recharge in the NERB are presented as a "best total" based on the cell-by-cell product of area and rate of recharge.

Table 6-3. Annual recharge statistics for NERB aquifer recharge zones (PRISM, 2013; Taboga and Stafford, 2016).

Aquifer recharge zone	Recharge zone surface area	Percentage of total basin surface area	"Best total" annual recharge volume	"Best total" recharge as percent of basin total	"Best total" average recharge depth	
	(acres)		(acre-feet)		(feet)	(inches)
Quaternary	249,022	5.09%	19,680	2.93%	0.079	0.95
Lower Tertiary System	2,466,913	50.46%	121,106	18.00%	0.049	0.59
High Plains System	576,948	11.80%	28,674	4.26%	0.050	0.60
Upper Cretaceous System	373,638	7.64%	18,451	2.74%	0.049	0.59
Other Cretaceous Aquifers	365,809	7.48%	54,458	8.09%	0.149	1.79
Paleozoic Aquifers	530,390	10.85%	191,062	28.40%	0.360	4.32
Precambrian Units	326,190	6.67%	239,313	35.57%	0.734	8.80
Total, Precambrian through Quaternary zones	**4,888,911**	**100.00%**	**672,744**	**100.00%**	**0.138**	**1.65**
Total, Sedimentary Aquifers (Paleozoic through Quaternary zones)	**4,562,721**	**75%**	**433,431**	**28%**	**0.057**	**0.68**