Chapter 6

Bear River Basin Hydrogeology and Groundwater Resources

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Wyoming's groundwater resources occur in both unconsolidated deposits and bedrock formations. In terms of frequency of use, the primary hydrogeologic unit in the Bear River Basin is the Quaternary Bear River alluvium (WWDO, 2012) (**Figs. 8-1** through **8-4; Pl. 6**). Additionally, over twenty bedrock aquifers, ranging in geologic age from Paleozoic to Tertiary (**Pls. 2** and **5**), exhibit heterogeneous permeability and provide variable amounts of useable groundwater.

Generally, aquifers are defined as geological units that store and transport useable amounts of groundwater while less permeable, confining units impede groundwater flow (**Section 5.1.1**). In practice, the distinction between aquifers and confining units is not so clear. A geologic unit that has been classified as confining at one location may act as an aquifer at another. Virtually all of the geologic units in the Bear River Basin, including confining units, are capable of yielding at least small quantities of groundwater. For example, the Green River Formation is classified as both an aquifer and a confining unit in the Bear River Basin, and several springs discharge water from this formation 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 Thaynes 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 the quality of a basin's groundwater resources.

One of the primary purposes of this study is to evaluate the groundwater resource of the Bear River Basin primarily through the following tasks (**Chapter 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

Although an enormous quantity of groundwater is stored in the Bear River groundwater basin, the basin's complex geology does not permit the use of the general assumptions regarding aquifer geometry, saturated thickness, and hydraulic properties. Hydrogeologists commonly employ these assumptions to calculate a plausible estimate of total and producible groundwater resources. The data required for a basin-wide, aquifer-specific assessment of groundwater resources is not available and is unlikely to ever be developed. Therefore, groundwater resources evaluated in this study rely on previous estimates (Hamerlinck and Arneson, 1998) of the percentage of precipitation in areas where aquifer units outcrop that will ultimately reach the subsurface as recharge (**Figs. 6-1** through **6-4**) and the formulation of a basin-wide water balance (**Chapter 8**). The technical and conceptual issues concerning recharge are discussed in **Section 5.1.3**.

Similarly, the extensive hydrogeologic data required to estimate the safe yield of groundwater for the entirety of the Bear River Basin does not exist. Furthermore, geoscience has evolved beyond the concept of safe yield since it was first introduced by Lee (1915), and many scientists and water managers have largely abandoned this principle in favor of concepts such as sustainable development. 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 outcrop areas

To begin the process of evaluating recharge, specific aquifers and groups of aquifers to which the recharge calculations will be applied must be distinguished (**Figs. 6-1** through **6-4**). Several previous studies (**Section 2.1**) have grouped the Bear River Basin's hydrogeologic units into various combinations of aquifers, aquifer systems, and confining units. The hydrostratigraphy developed for this study is based on previous regional assessments and is summarized in the hydrogeology map illustrated in **Plate 2** in the hydrostratigraphic charts shown on **Plate 5**, and in **Chapter 7**. The hydrostratigraphic charts in **Plate 5** 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 shown on **Plate 2**.

Section 5.2 discusses how the map units of Love and Christiansen (1985), previously 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 not able to distinguish all stratigraphic units present in the Bear River Basin due to the sheer size of the dataset and cartographic limitations. Therefore, some geologic units were not mapped individually but instead, are shown on **Plate 2** as undifferentiated hydrogeologic units. To address this deficit, the outcrops of hydrogeologic units that were assigned as aquifers or aquifer groups (**Pl. 2**) are aggregated by geologic age (**Pl. 2**). These aggregated aquifers, or aquifer recharge zones, were generated as GIS shapefiles and used to calculate recharge volumes and rates:

- Quaternary aquifers (**Fig. 6-1**)
- Tertiary aquifers (**Fig. 6-2**)
- Mesozoic aquifers (**Fig. 6-3**)
- Paleozoic aquifers (**Fig. 6-4**)

Precambrian formations, buried more than 25,000 feet below the surface in the Wyoming portion of the Bear River Basin consist primarily of quartzite, gneiss, and schist (Royce, 1993). These units function as a regional confining unit and do not contribute to groundwater supplies.

6.2 Average annual recharge

Only a fraction of the groundwater stored in the Bear River Basin can be withdrawn for beneficial use because groundwater naturally discharges to streams, springs, lakes, and wetlands and is further lost through evapotranspiration. Under natural conditions, a state of dynamic equilibrium in which natural discharges to surface waters and evapotranspiration are counterbalanced by recharge exists. In effect, this balance means that higher rates of recharge result in higher levels of natural discharge over time. Withdrawals from wells and springs remove groundwater from aquifer storage and natural discharges. Thus, without careful management, over time flows in springs, streams, and wetlands, as well as aquifer storage, will be depleted to such a degree that water rights holders will not receive their full appropriation and riparian ecosystems will collapse. This risk has long been recognized by Wyoming's agricultural community, as well as water managers for municipalities and conservation districts, state water administrators, and legislators. The connection between surface water and groundwater resources has been incorporated into Wyoming's water law and also forms one of the core tenets in forming Wyoming's interstate water compacts, including the Bear River Compact (**Appendix D**).

To evaluate recharge on a regional scale, this study combines estimated, average annual recharge data from the Spatial Data and Visualization Center (SDVC) (Hamerlinck and Arneson, 1998) and WSGS maps illustrating where pertinent hydrogeologic units outcrop in the Bear River Basin (**Pl. 2; Figs. 6-1** through **6-4**). As with the original SDVC study (Hamerlinck and Arneson, 1998), this report does not consider artificial recharge from lawn and crop irrigation, surface water diversions and flow between aquifers in poorly completed wells. It should be noted; however, that artificial recharge, particularly from crop irrigation and irrigation diversion structures, may be substantial in the alluvial aquifers of the Bear River Basin (Forsgren and Associates, 2001; WWDO, 2012).

Withdrawal and consumptive use data from the 2011 Bear River Basin Report (WWDO, 2012 page 44, Tables 5-4 and 5-5) indicate that approximately 8,000 acre–feet of irrigation water returns to the watershed in the form of recharge or as direct return flows to streams. Currently, it is not possible to quantify the amounts that recharge

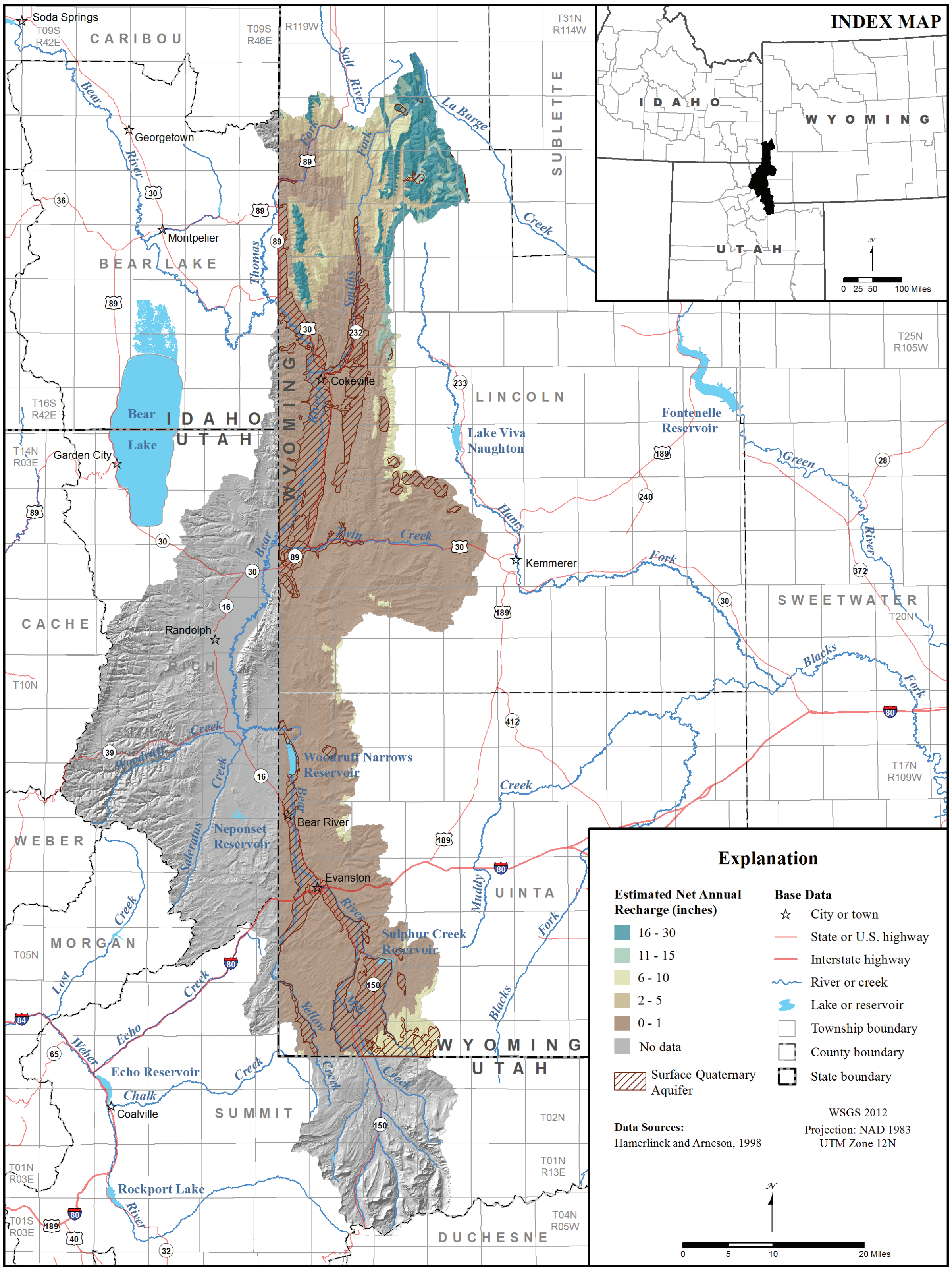

Figure 6-1. Estimated net annual aquifer recharge – surface Quaternary aquifer, Bear River Basin, Wyoming.

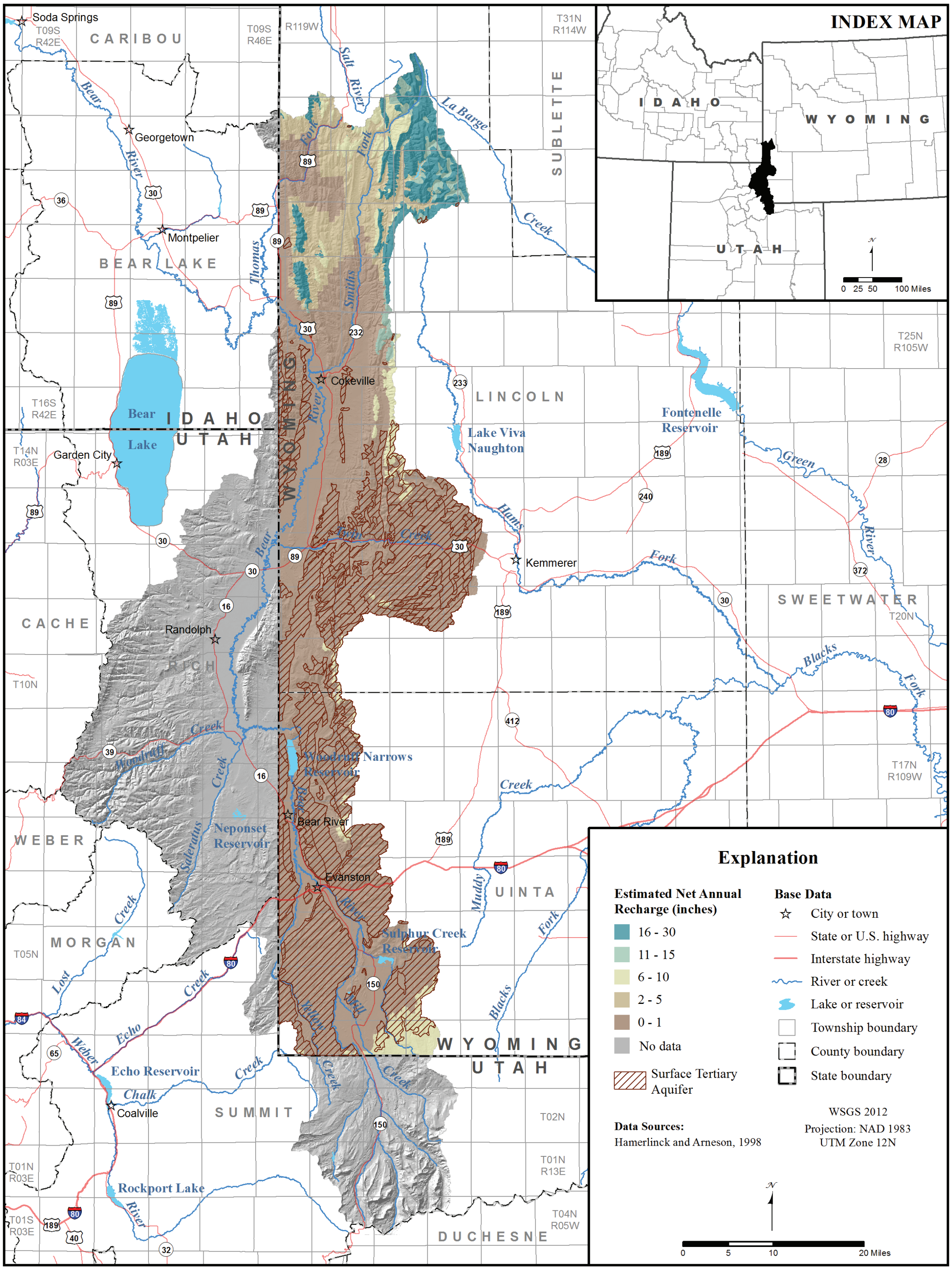

Figure 6-2. Estimated net annual aquifer recharge – surface Tertiary aquifer, Bear River Basin, Wyoming.

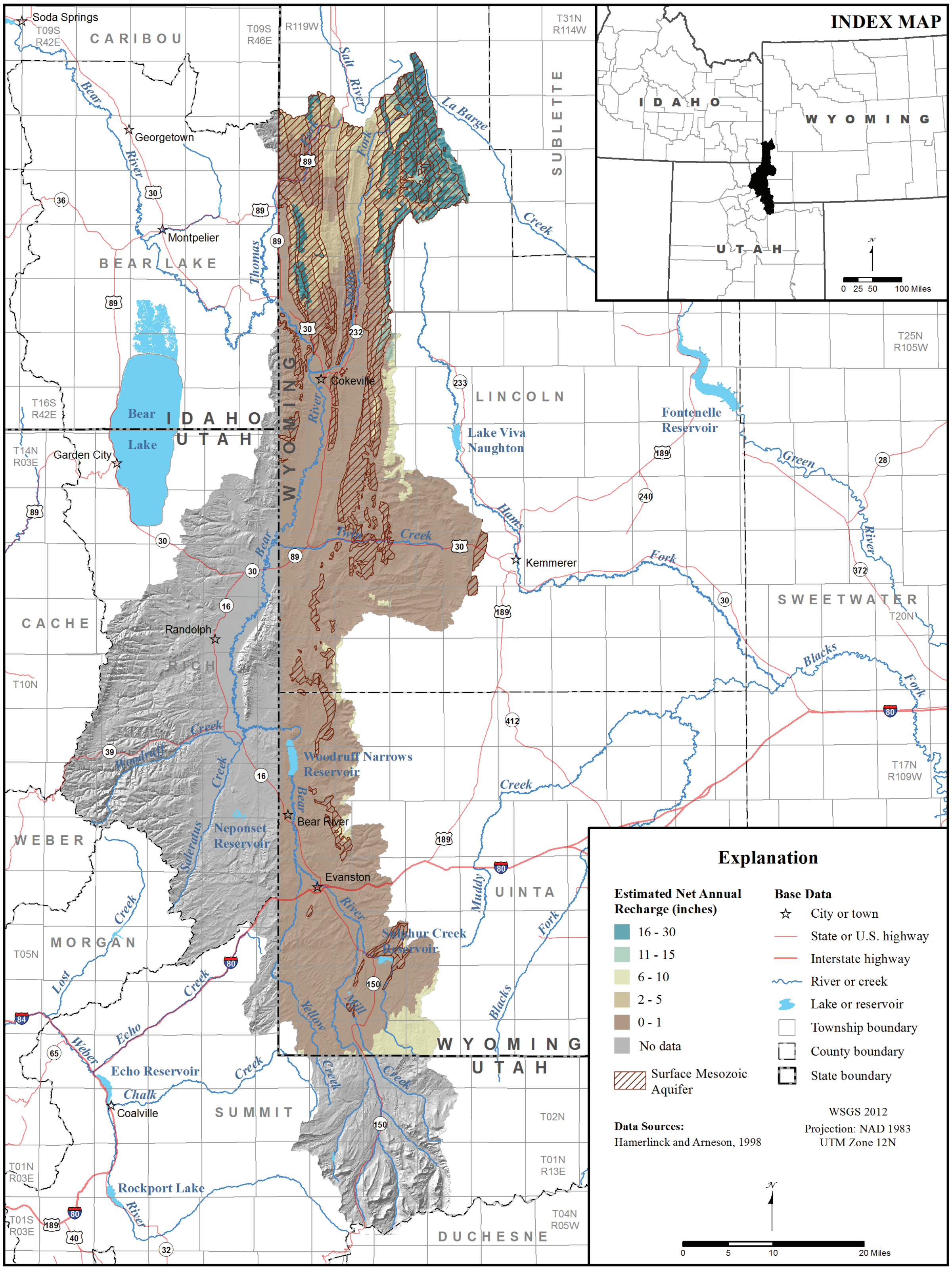

Figure 6-3. Estimated net annual aquifer recharge – surface Mesozoic aquifer, Bear River Basin, Wyoming.

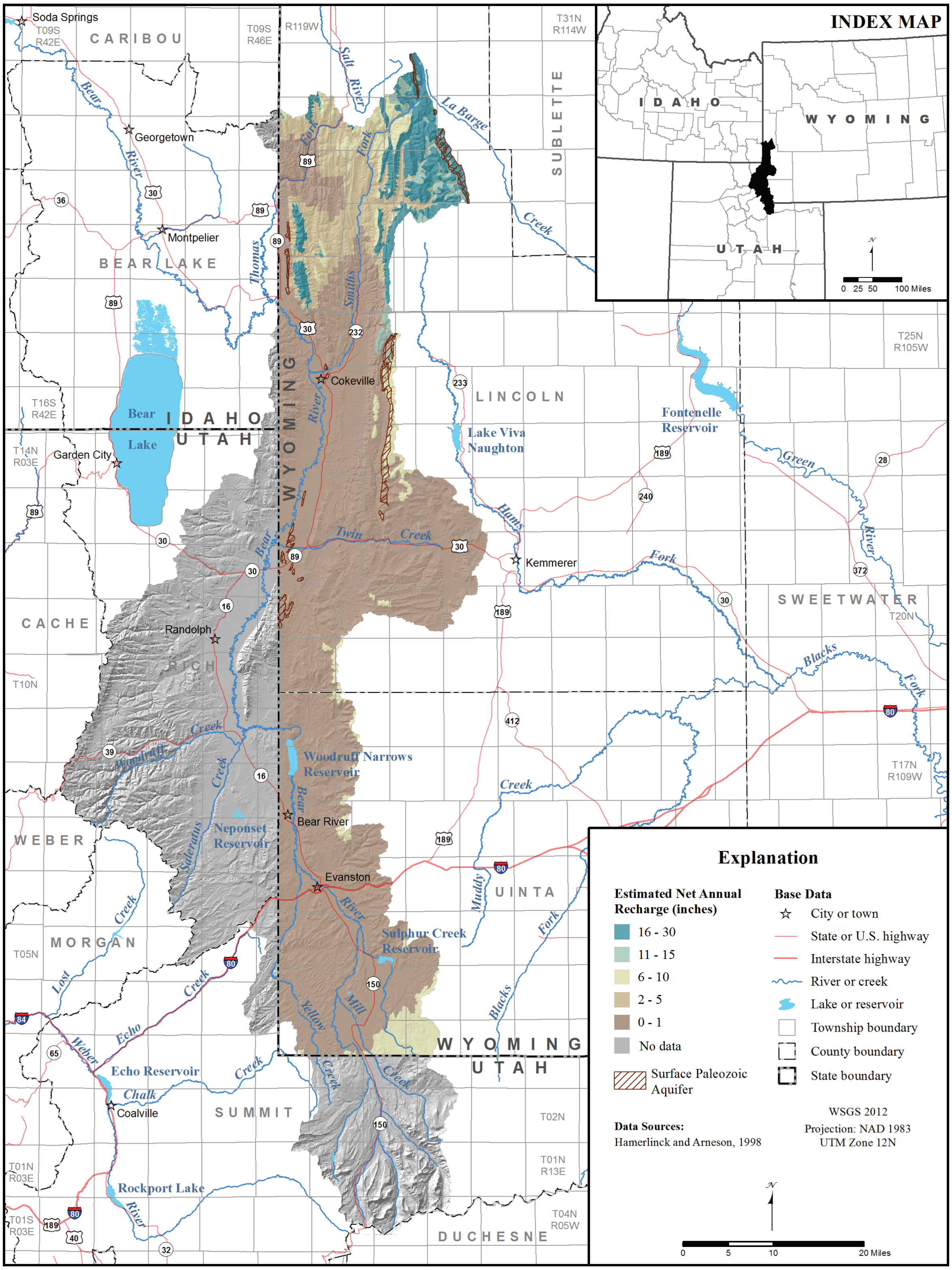

Figure 6-4. Estimated net annual aquifer recharge – surface Paleozoic aquifer, Bear River Basin, Wyoming.

underlying aquifers as opposed to those that return as direct surface flows. Furthermore, it is likely that a substantial portion of artificial recharge from irrigation becomes baseflow to the Bear River and its tributaries because most irrigated lands overlie alluvial deposits (Tab E, Figure 1 - Forsgren and Associates, 2001). The potentiometric surface map shown on **Plate 6** of this report indicates that groundwater flows to gaining reaches along much of the Bear River mainstem.

Even so, average annual recharge constrained by best estimates of annual discharge (both natural and by pumping) and periodic water level monitoring provide valuable baseline data. These data assist in establishing 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 Bear River Basin water plans (Forsgren and Associates, 2001; WWDO, 2012) 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 Bear River Basin ranges from less than one inch per year in the basin interior to over thirty inches per year in the surrounding mountains (Hamerlinck and Arneson, 1998). Mountains and foothills receive more recharge than basin lowlands due to environmental attributes characteristic of highland zones:

- Greater amounts of precipitation and more persistent snow pack (**Fig. 3-3**)
- More abundant vegetation
- Soil and vegetation combinations more favorable to infiltration
- Lower rates of evapotranspiration
- Better exposure of the upturned and weathered edges of hydrogeologic units facilitates infiltration because zones of higher permeability often parallel bedding
- The presence of structural features that enhance recharge (e.g., faults, fractures, joints, fault/fracture-controlled surface drainages)

Figure 6-5 shows how recharge efficiency, defined as a percentage of average annual precipitation (R/P), varies throughout the Wyoming portion of the Bear River Basin and suggests what environmental factors exert control on recharge. Recharge is most efficient in the mountains of the Tunp, Sublette, and Wyoming ranges and the foothills of the High Uinta Mountains, but recharge rates are also slightly higher west and southwest of Evanston. The dataset for **Figure 6-5** was generated by dividing 4,000-meter grid cells and assigning values for average annual aquifer recharge (**Fig. 5-1**) and average annual precipitation (**Fig. 3-3**) to each cell; both data sets were obtained from the SDVC aquifer vulnerability study prepared for the State of Wyoming (Hamerlinck and Arneson, 1998).

Average annual recharge (**Fig. 5-2**) is based on percolation percentages for different soil/vegetation combinations multiplied by average annual precipitation for the 30-year period from 1981 to 2010. Total average annual precipitation has been estimated (PRISM, 2013) as 2,640,125 acre-feet for the larger Bear River Basin shown in Figure 3-3 and 1,398,194 acre-feet for 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 probably 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 6-5**. However, as discussed previously (**Sections 5.1.3.1** and **5.4**), local recharge rates may be dominated by site-specific hydrogeologic conditions (e.g., solution-enhanced fracture permeability). Lastly, Hamerlinck and Arneson (1998) indicated that many areas in the basin interior receive zero or, in some cases, negative amounts of recharge. In this report these areas were treated as receiving zero recharge; negative values were not subtracted from the total.

Table 6-1 shows the percentage of surface area by

Table 6-1. Percent of aquifer recharge zones recharging at varying efficiencies.

Recharge Efficiency as annual recharge / annual precipitation, (in percent)	0-1	2	5	6	10	30	35	60
Quaternary	57.61	0.00	27.37	7.09	0.00	0.00	7.53	0.39
Tertiary	17.29	8.68	0.93	67.94	0.06	0.00	5.07	0.03
Mesozoic	25.97	0.00	0.38	41.48	0.28	5.71	4.28	21.89
Paleozoic	37.56	0.00	0.46	10.64	-	-	21.71	29.63

specified range of recharge efficiency, as R/P and as determined via GIS analysis, for each of the four, age-classified, aquifer recharge zones (**Figs. 6-1** through **6-4; Pl. 2**).

Table 6-1 shows that most recharge to all aquifer recharge zones in the Bear River Basin occurs at the lowest range of recharge efficiency (0-10 percent of precipitation). Higher proportions of Mesozoic and Paleozoic aquifers receive recharge at efficiencies greater than 10 percent, likely due to the elevation of older aquifers exposed in upland areas. The consistently low recharge efficiencies calculated for Tertiary and Quaternary aquifer zones may reflect the subdued relief and aridity (**Fig. 3-3**) within the interior of the Bear River Basin.

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)

The outcrop areas assigned to aquifer groups in the recharge calculations (**Figs. 6-1** through **6-4**) were determined from the hydrogeologic map (**Pl. 2**) developed for this study. Average annual rates of recharge throughout the Bear River Basin (mapped in 100-meter cells) adapted from the Wyoming Groundwater Vulnerability Assessment Handbook (Hamerlinck and Arneson, 1998) are shown in **Figure 5-1**. Recharge rates were grouped into the five ranges to make **Figure 5-1** more readable and to mitigate the 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.

These recharge calculations do not incorporate confining unit outcrop areas (**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 outcrop areas provide a more conservative estimate of available groundwater resources. Furthermore, leakage from adjacent confining layers was also disregarded in this evaluation.

Table 6-2 summarizes calculated recharge for the Bear River Basin over the ranges of average annual recharge mapped on **Figure 5-2** and the aquifer recharge zones displayed in **Figures 6-1** through **6-4**. A "best total" amount for each range of recharge over the outcrop area of each aquifer group is provided in **Tables 6-2** and **6-3** based on the recharge area for each whole inch of recharge in the database compiled for this study. "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

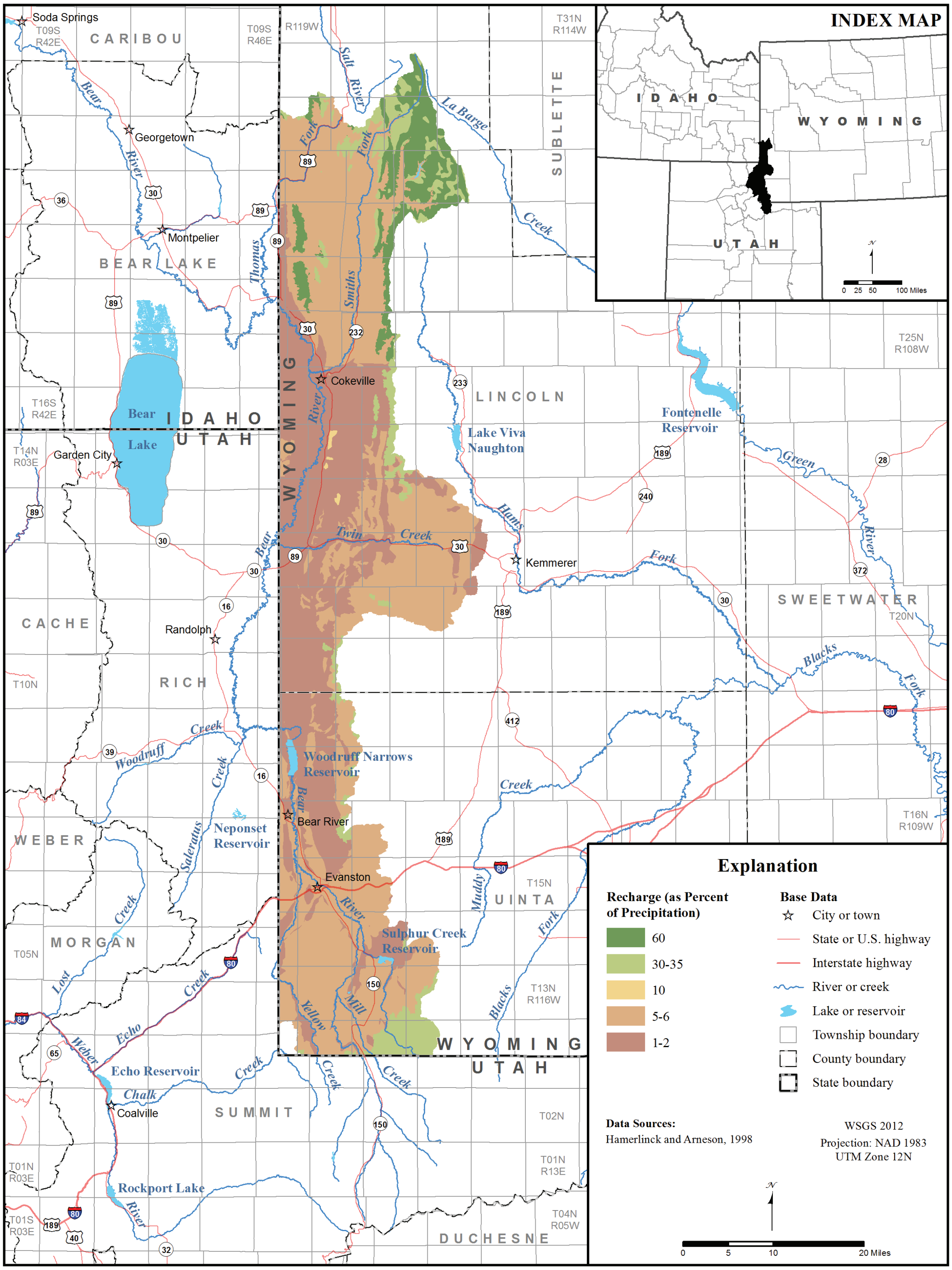

Figure 6-5. Aquifer recharge as percentage of precipitation using 1981 - 2010 precipitation normals, Bear River Basin, Wyoming.

Table 6-2. Bear River Basin average annual recharge calculations

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Average Annual Recharge
	Inches	Feet	Acres	Best Total (Acre-feet)
Quaternary	0	0.00	107,991	0
	1 5	0.08 0.42	48,565	4,111
	6 10	0.50 0.83	12,100	8,191
	11 15	0.92 1.25	862	868
	16 25	1.33 2.08	515	885
	TOTAL		170,033	14,055

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Range - Average Annual Recharge
	Inches	Feet	Acres	Best Total (acre-feet)
Mesozoic	0	0.00	67,916	0
	1 5	0.08 0.42	110,286	13,754
	6 10	0.50 0.83	16,839	12,535
	11 15	0.92 1.25	12,566	13,510
	16 29	1.33 2.42	53,700	88,229
	TOTAL		261,307	128,029

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Average Annual Recharge
	Inches	Feet	Acres	Best Total (acre-feet)
Tertiary	0	0.00	105,624	0
	1 5	0.08 0.42	273,508	22,921
	6 10	0.50 0.83	19,628	11,611
	11 15	0.92 1.25	267	261
	16 28	1.33 2.33	93	148
	TOTAL		399,120	34,940

ERA	Range of Average Recharge per year		Outcrop Area Receiving Recharge	Range - Average Annual Recharge
	Inches	Feet	Acres	Best Total (acre-feet)
Paleozoic	0	0.00	6,613	0
	1 5	0.08 0.42	2,153	650
	6 10	0.50 0.83	2,520	1,331
	11 15	0.92 1.25	1,548	1,651
	16 37	1.33 3.08	4,053	8,312
	Low TOTAL		16,886	11,944

Bear River Basin TOTAL	847,346	188,968

[1] adapted from Hamerlinck and Arneson, 1998 and [2] PRISM, 2013

Table 6-3. Annual recharge statistics for Bear River Basin aquifer recharge zones.

Aquifer Recharge Zone	Recharge zone surface area (acres)	Percent of total basin surface area	"Best total" annual recharge volume (acre-feet)	"Best total" recharge as percent of basin total	"Best total" average recharge depth, in	
					feet	inches
Quaternary	170,033	20.07%	14,055	7.44%	0.083	1.0
Tertiary	399,120	47.10%	34,940	18.49%	0.088	1.1
Mesozoic	261,307	30.84%	128,029	67.75%	0.490	5.9
Paleozoic	16,886	1.99%	11,944	6.32%	0.707	8.5
Total, Paleozoic through Quaternary zones	**847,346**	**100.00%**	**188,968**	**100.00%**	**0.223**	**2.7**

each aquifer recharge zone. An analysis of average recharge depths shows that high elevation Paleozoic aquifers receive 0.707 feet (8.5 inches) of recharge compared to about 1 inch in Quaternary and Tertiary aquifers. The Mesozoic aquifers, which crop out in highland areas located primarily in northern and central parts of the basin (Pl. 2), receive 0.49 feet (~5.9 inches) of recharge. Coupled with the fact that they are also areally extensive, covering about 31 percent of the basin's surface area, infiltration through Mesozoic strata provides about 68 percent of the basin's recharge.

Table 6-2 illustrates that, predictably, recharge volume percentages are generally consistent with the surface areas of the aquifer recharge zones. Although the Tertiary aquifers (**Fig. 6-2**) constitute the largest aquifer recharge area *(*over 624 square miles*)*, they receive the second largest volume (39,341 acre ft/year) of recharge. The Mesozoic group (**Fig. 6-3**) outcrops over 408 square miles but receives the highest amounts of annual recharge (130,858 acre-ft/year). Quaternary aquifers (**Fig. 6-1**) receive 18,554 acre-ft of recharge annually. The Paleozoic aquifers (**Fig. 6-4)** constitute the smallest aquifer recharge area (26 square miles) and receive the smallest recharge volume (11,944 acre-ft/year) in the Bear River Basin.

In the Wyoming part of the Bear River Basin, the best estimate of total recharge is 188,968 acre- feet, or 13.5 percent, of total precipitation. Notably, this value approaches the "rule-of-thumb" frequently cited by water resource professionals: approximately ten percent of precipitation will eventually become recharge. Finally, the volumes of recharge that enter groundwater storage are further reduced in areas where recharge is "rejected" or discharged as spring flow. Once rejected, it may be evaporated, beneficially used or discharged as streamflow.

6.3 Summary

- Recharge is ultimately controlled by precipitation. Total average annual precipitation for the tri-state Bear River Basin (**Fig. 3-2**) has been estimated as 2,640,125 acre-feet and 1,398,194 acre-feet for the Wyoming portion of the basin (**Table 8-2a**).

- Recharge controlled by precipitation and soil/vegetation combinations in the Wyoming portion of the Bear River Basin ranges from 0 to 37 inches (Hamerlinck and Arneson, 1998), with the lowest values occurring in the interior basins and the highest values in the surrounding mountain ranges.

- Recharge efficiency (recharge as a percentage of precipitation, or R/P) varies based on the factors used the Wyoming Groundwater Vulnerability Assessment Handbook (Hamerlinck and Arneson, 1998) to estimate recharge throughout Wyoming.

- 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 upturned Mesozoic and Paleozoic aquifers in the uplifted and mountainous areas. Recharge in the Bear River Basin is most efficient in higher mountain, Paleozoic terrains.

- Recharge to Precambrian formations was not evaluated because, considered together, these units act as a regional confining unit. Because Precambrian rocks are buried deeply below younger sedimentary formations, they do not supply groundwater in the Bear River Basin.

- Estimates of average annual recharge in the Bear River Basin are presented as a “best total” based on the cell-by-cell product of area and rate of recharge.