Chapter 5

Technical concepts: Hydrogeology and groundwater quality

Karl Taboga, Timothy T. Bartos, Paul Taucher, Jim Stafford, Melanie L. Clark, and Laura L. Hallberg

This chapter discusses the technical concepts and terminology used in this study. Additional discussions and illustrations of the concepts commonly used in the study of groundwater resources can be found in U.S. Geological Survey (USGS) Water Supply Paper 2220 (Heath, 1983). *Hydrogeology* is the area of geology that studies the distribution and movement of groundwater through the bedrock and unconsolidated material (including soil) of the Earth's crust. In contrast, the term *geohydrology*, which is often used interchangeably, more properly describes a branch of engineering that studies subsurface fluids. Groundwater hydrology is deemed by the USGS to be the branch of hydrology concerned with the occurrence, movement, and chemistry of groundwater. The study of groundwater resources is an interdisciplinary field that requires extensive knowledge of geology along with an understanding of the basic principles of physics, chemistry, mathematics, biology, and engineering. The hydrogeologist must be able to understand the intricate physical and chemical interactions that occur between groundwater, host rock units, unconsolidated materials, minerals, and the surface environment.

Hydrogeology usually deals with groundwater that is accessible and can be directly used for the benefit of society. Shallow groundwater resources (e.g., water-table and shallow, confined aquifers) and their interactions with surface waters are of interest to geologists, water managers, soil scientists, agriculturalists, hydrologists, water law attorneys, civil engineers, and citizens who use these resources for their water supplies. Groundwater in deeper formations may be relatively inaccessible to the water well driller or, more often, of a quality that is too poor to use for potable water supply. The hydrogeology of these formations may still be important to mineral and petroleum resource geologists, geophysicists, and petroleum engineers. The suitability of groundwater for a particular beneficial use depends primarily on water quality. In this study, groundwater quality is evaluated relative to its suitability for domestic, irrigation, and livestock use, based on the Environmental Protection Agency's (EPA) Safe Drinking Water Act (SDWA) and the Wyoming Department of Environmental Quality's (WDEQ) class-of-use, water-quality standards (**section 5.5.1**; **chapter 7**). Aquifer sensitivity, potential sources of groundwater, and state and federal programs designed to characterize and protect groundwater quality in Wyoming are also discussed in this chapter.

5.1 Definitions and concepts

The movement of groundwater through, and its chemical interaction with, permeable earth materials is complex. Highly variable geologic and hydraulic properties within an aquifer control flow, chemical composition, and availability. Fundamentally, groundwater is a slow-moving, viscous fluid that flows through interconnected voids in the host rock along pressure gradients (areas of high hydraulic pressure to areas of lower hydraulic pressure). The voids may consist of pores between individual mineral grains (i.e., intergranular space), fractures of varying size, faults, dissolution features such as tunnels and caves, vesicles in volcanic rocks, or some combination of these. Voids range in size from microscopic to cavernous. Groundwater chemistry is determined by the mineral composition of the aquifer system and the residence time that the water is in contact with the earth materials through which it flows. Groundwater residence times can range from a few days, to hundreds of thousands of years.

5.1.1 Definitions

The following technical terms and concepts are either used in this study or have been provided to supplement the reader's understanding:

Geologic unit - a geologic formation, member, lens, tongue, bed, flow, other stratigraphic unit or group of rocks that have been correlated, named, and mapped by geologists based on lithological and geospatial continuity and other properties. With the development of Geographic Information Systems (GIS) technology, Wyoming's geologic units have been compiled into a database that can be modified, queried, and mapped based on specified geospatial, physical, and chemical criteria, such as the hydrologic characteristics described in this study. An additional discussion on geologic units is provided in **section 5.2**.

Lithostratigraphic unit – a mappable stratigraphic unit defined by lithologic uniformity and continuity. Lithostratigraphic and, to a lesser degree, other stratigraphic units are the most commonly characterized components of geologic units and are generally used in geologic mapping where allowed by the map scale. An additional discussion of lithostratigraphic units is provided in **section 5.2**.

Hydrogeologic unit – one or more adjacent geologic units, or parts of geologic units (e.g., *lithostratigraphic units*), grouped according to their hydrologic characteristics, such as whether the designated unit functions as an *aquifer* or a *confining unit*.

Aquifer – a *geologic unit*, group of *geologic units*, or part of a *geologic unit* that contains adequate water-saturated and permeable materials to yield sufficient quantities of water to wells and springs (modified from Lohman and others, 1972), with "sufficient" generally defined in terms of ability to meet specified uses. Aquifers both store and convey groundwater. Aquifers are not defined on the basis of geologic unit boundaries, but on the hydraulic characteristics, common recharge-discharge areas, and mechanisms of the units that compose them.

Aquifer system – a heterogeneous body of saturated, interbedded geologic units with variable permeability that operates regionally as a major, integrated, water-bearing *hydrogeologic unit*. An aquifer system comprises two or more smaller aquifers separated, at least locally, by strata with low permeability that impede groundwater movement between the component aquifers but do not preclude the regional hydraulic continuity of the system (modified from Poland and others, 1972). *Aquifers* and aquifer systems are generally anisotropic because of interbedded low-permeability strata (e.g., shale, claystone, mudstone, bentonite, and evaporites). Most aquifer systems also share the following characteristics:

- Regionally extensive,
- Common recharge and discharge areas and mechanisms,
- Similar hydraulic properties,
- Similar water-quality characteristics, and
- Hydraulically isolated from younger and older aquifers/aquifer systems by thick and laterally extensive confining units.

Confining unit – a geologic unit, group of units, or part of a unit with very low *hydraulic conductivity* that impedes or precludes groundwater movement between the *aquifers* it separates or between an *aquifer* and the ground surface. The *hydraulic conductivity* of a confining unit may range from essentially zero to any value substantially lower than that of an adjacent aquifer. Confining units are conventionally considered to be impermeable to groundwater flow, but most leak water at low to very low flow rates. Given large areas and extended periods of time, confining units can ultimately leak significant quantities of water.

Confined aquifer – an *aquifer* overlain and underlain by *confining units* that limit groundwater flow into and out of the aquifer. Confined aquifers are completely saturated and under *artesian* pressure. An aquifer can be semi-confined if there is sufficient leakage through the adjacent *confining unit*(s).

Unconfined aquifer – the water-saturated part of a *hydrogeologic unit* that contains groundwater under atmospheric pressure and thus rises and falls relatively quickly in response to *recharge* (e.g., precipitation, irrigation, or waste disposal) and changes in atmospheric pressure. Unconfined aquifers are generally saturated only in the lower part of the host *hydrogeologic unit*.

Alluvial aquifer – an *aquifer* composed of loose, unconsolidated sediments deposited along a streambed. Alluvial aquifers usually possess high degrees of hydrologic variability over short distances because the component clays, silts, sand, gravel, cobbles, and boulders were unevenly deposited under shifting climatic and hydrologic conditions.

Bedrock aquifer – an *aquifer* that occurs within a consolidated rock unit. Groundwater is stored and transported within the pores of the solid rock, fractures, solution cavities, or any combination thereof.

Unconsolidated aquifer – a water-bearing unit in loose, uncemented sediments such as sand, gravel, clays, and silts.

Colluvium – Loose, unconsolidated earth materials deposited primarily by gravity at the foot of a hillslope including talus and cliff debris.

Perched groundwater or a *perched aquifer* – an unconfined lens of groundwater, generally limited in lateral extent, lying on top of a *confining unit* in a configuration similar to ponding. Perched groundwater generally occurs at shallower depths hydraulically unconnected to deeper, more laterally extensive, *unconfined* or *confined aquifers*.

Potentiometric surface – a surface that represents the *total head* in an aquifer. Within a *confined aquifer*, it is a conceptual surface defined by the level to which water rises in wells that penetrate that aquifer. Within an *unconfined aquifer,* the conceptual surface corresponds to an actual, physical surface. *Potentiometric surface* has generally replaced the older terms *piezometric surface* and *water table*, and *groundwater surface* is a more up-to-date synonym. The *potentiometric surface* is generally mapped by equal-elevation contours in feet above mean sea level.

Water table – the groundwater surface within an unconfined aquifer under atmospheric pressure. Although the water table is often considered the top of the zone of saturation, it is more correctly considered the surface where pore-water pressure equals atmospheric pressure. While the *capillary fringe* above the water table is saturated, it is below atmospheric pressure and thus fails to meet the definition of the water table. The term water table implies a flat, horizontal surface, but the actual surface is tilted or contoured like the land surface. In colloquial usage, the water table is the first occurrence of unconfined groundwater encountered at depth and is generally equivalent to groundwater surface or *potentiometric surface*.

Capillarity – the effect of surface tension and molecular attraction between liquids and solids that causes water within the vadose zone (above the water table) to be at less than atmospheric pressure. Groundwater in the *capillary fringe* immediately above the *water table* will be drawn upward by this effect.

Vadose zone – the depth interval between the ground surface and the water table that can include: 1) unsaturated soils, unsaturated bedrock, and unconsolidated materials such as alluvium, *colluvium*, and weathered bedrock, and 2) the *capillary fringe* immediately above the water table.

Hydraulic gradient – the change in *total head* per unit distance measured in the direction of the steepest slope of the groundwater (potentiometric) surface. Hydraulic gradient has both direction and magnitude and is commonly expressed in feet of elevation change per foot of horizontal distance (ft/ft). The direction of maximum slope on the *potentiometric surface* (or normal to lines of equal elevation on the potentiometric surface), from high to low elevation, indicates the direction that groundwater will flow along permeable, interconnected pathways within isotropic and homogeneous earth materials.

Total head – the height of a column of water above a datum due to a combination of elevation head and pressure head.

Static head or *static water level* – the level of water in a well when neither the well nor surrounding wells are being pumped and the *total head* in the aquifer is generally at equilibrium. Static head/water level is commonly expressed in feet of elevation above mean sea level.

Drawdown – the lowering of the groundwater potentiometric surface (total head) by discharge from an aquifer (pumping or natural outflow) expressed in feet of water level change. A rise in groundwater level is the opposite of drawdown.

Recharge – water that infiltrates at ground surface, penetrates the *vadose zone*, and reaches the *water table*.

Discharge – groundwater that flows from an aquifer. Discharge from an aquifer can occur naturally by flow into streams or lakes, by leakage into adjacent geologic or hydrogeologic units, by flow from springs, by near-surface evapotranspiration or artificially, by pumping wells.

Evapotranspiration – the loss of water from the near-surface vadose zone to the atmosphere by the combined processes of evaporation (direct vapor-phase transfer from the soil) and transpiration (transfer through plant root systems and respiration).

Porosity (total) – the proportion of void or open-space volume (e.g., intergranular space, fractures, solution cavities) in a total volume of earth material (e.g., soil, unconsolidated deposit, bedrock), generally expressed as a percentage or decimal fraction.

Effective porosity – the proportion of the *total porosity* in a volume of earth material that is interconnected and allows the flow of groundwater. Water attached to solid surfaces within the interconnected *porosity* decreases effective porosity. Effective porosity is always less than total porosity.

Storage (total) – the total volume of groundwater contained within a volume of earth material – equal to saturated volume times porosity. Storage changes in response to recharge and discharge.

Hydraulic conductivity – the capacity of earth materials to transmit groundwater, expressed as a measure of the amount of water that can flow through the interconnected open spaces of earth materials (often expressed as gallons per day, per square foot: gpd/ft^2), or in terms of velocity (ft/day). Hydraulic conductivity is dependent on the physical characteristics of both the porous earth material and the fluid, and can be as variable as the lithologies that compose the Earth's crust. This parameter can vary in any direction, but it is commonly much higher parallel to than across stratification.

Permeability – differs from *hydraulic conductivity* in that it depends only on the characteristics of the porous material. The dimensions of permeability are length squared (ft^2, cm^2, m^2, etc.). Permeability is the parameter preferred by the oil and gas industry where it is more practical for evaluating multi-phase fluid (oil, gas, water) flow.

Transmissivity – the rate at which groundwater moves through a unit width of the water-saturated portion of the aquifer, under a unit *hydraulic gradient* expressed in square feet per day (ft^2/day = ft/day <u>x ft</u>) or gallons per day, per foot (gpd/ft = gpd/ft^2 <u>x ft</u>). Transmissivity is equivalent to the *hydraulic conductivity* integrated over the thickness of an aquifer (<u>x ft</u> = aquifer thickness).

Specific capacity – the pumping discharge rate of a well divided by feet of *drawdown* of the water level in the well during pumping, commonly expressed in gallons per minute, per foot of *drawdown* (gpm/ft).

Specific yield – the drainable *porosity* of an *unconfined aquifer*, reported as a ratio of the volume of water that will drain under gravity, to the volume of saturated earth material. Specific yield is a dimensionless parameter that is commonly used to describe the proportion of *aquifer* material volume that provides water available for beneficial use. Compare specific yield to *porosity* and *effective porosity*: All three are dimensionless but multiplied by the volume of the saturated rock, *porosity* will equal total void space, *effective porosity* will return total groundwater volume, and specific yield will return the volume of available groundwater (**section 5.1.4**).

Storage coefficient – the volume of water released from or taken into storage per unit surface area of the aquifer, per unit change in *total head*. Like *specific yield*, storage coefficient is a dimensionless parameter—the numerator and denominator cancel. In an *unconfined aquifer*, the water released from storage is from gravity drainage and the storage coefficient is essentially equivalent to *specific yield*. In a *confined aquifer*, water released from storage, also called *specific storage*, comes primarily from expansion of the water and compression of the *aquifer* as pressure is relieved during pumping. Because of the difference in mechanics of how water is released from storage, the storage coefficients of *unconfined aquifers* (0.1 to 0.3) are generally several orders of magnitude larger than those of *confined aquifers* (10^{-5} to 10^{-3}).

Specific retention – the ratio of the volume of water retained in the pores of an unconfined aquifer after gravity drainage to the total volume of earth material. Specific retention is a dimensionless parameter expressed as a percentage.

Well yield – the rate of groundwater discharged (pumped or flowing) from a well expressed in gallons per minute (gpm).

Artesian flow – occurs where the *potentiometric surface* of a *confined aquifer* is at a higher elevation than the top of the *aquifer*. Water in wells at these locations will rise above the top of the *aquifer* to the level of the *potentiometric surface*.

Gaining stream – a surface water stream or part of a stream, which receives *discharges* of groundwater from the underlying or adjacent *hydrogeologic unit*(s). Surface water flow attributed to groundwater is commonly referred to as *baseflow*.

Losing stream – a surface water stream or part of a stream, which *recharges* the underlying or adjacent *hydrogeologic unit*(s) resulting in decreased, downstream flow.

Total dissolved solids (TDS) – a measure of the total concentration of minerals dissolved in groundwater, generally expressed in either milligrams per liter (mg/L) or parts per million (ppm). Generally mg/L is equivalent to ppm.

Geochemical water type – an expression of the dominant cations and anions dissolved in the groundwater.

5.1.2 Types of groundwater flow

Groundwater flow can be characterized as porous flow, conduit flow, fracture flow, or some combination of these three types:

- *Porous flow* occurs through open, interconnected, intergranular spaces (pores) within a sedimentary geologic unit (generally conglomerate, sandstone, siltstone, or unconsolidated deposits) or through intercrystalline pore spaces within igneous or metamorphic rocks. The size of the sediment grains or mineral crystals affects porous flow. Larger open pores between larger grains (or crystals) are generally more conducive to flow than smaller grains/pores. In an aquifer with a wide range of grain sizes (poorly sorted), the fine-grained material fills in the larger pore spaces and reduces flow toward that of a fine-grained aquifer. Porous flow is also referred to as *primary porosity,* i.e., the porosity that results from deposition of the sediments and subsequent diagenetic processes such as compaction and cementation of the rock matrix.

- *Conduit flow* occurs through large, discrete openings (pipes, cavities, channels, caverns, and other karstic zones), generally within relatively soluble sedimentary or evaporitic rocks such as limestone or dolomite, gypsum, anhydrite, or halite. Conduits form by the dissolution of soluble minerals in bedrock or by subsurface sediment transport (piping) through unconsolidated or loosely consolidated material.

- *Fracture flow* occurs through interconnected partings in bedrock: fractures and joints developed during structural deformation (folding, faulting), expansion (rapid overburden erosion) or compaction, (rapid deposition), physiochemical alteration (shrinkage during desiccation, bedrock weathering, soil formation) or thermal contraction (fractured and columnar basalts). Fractures occur either along or across existing bedding planes or other types of geologic contacts. The *porosity* of conduits and fractures is referred to as *secondary porosity,* although, frequently, conduits and fractures within a unit can transport water several times faster than the primary porosity in many aquifers.

5.1.3 Groundwater recharge, discharge, and flow

Groundwater systems at all scales, from local unconfined aquifers to entire groundwater basins, are defined by the physical factors that determine recharge, storage, and flow through the system to discharge areas. **Figure 5-1** is a cross section that illustrates some of the concepts discussed in this and other sections of this study.

5.1.3.1 Groundwater recharge

The accumulation of groundwater within an aquifer requires, first, a source of water and in shallow aquifers, that source is ultimately precipitation. Initially, precipitation will infiltrate at the ground surface, percolate through the unsaturated, or vadose, zone, and enter the water table. This process, alone, can take days to hundreds of years before the precipitation enters a receiving aquifer as "recharge." The path groundwater travels from there, however, can be complicated further by moving between aquifers and confining units depending on the flowpaths within a particular system. Understanding the sources, amount and delivery timing of recharge is essential to effectively characterize any groundwater resource. Despite its importance, recharge is one of the most difficult parameters to accurately quantify. Recharge cannot be measured directly, but is estimated indirectly using tools such as chemical or heat tracers, water budget calculations, or groundwater level analyses (Healy and Scanlon, 2010).

In the relatively dry climate of Wyoming, the mountain ranges surrounding the basins receive high levels of precipitation (**fig. 5-1**) and serve as significant sources of recharge. Consequently, the most important recharge areas in Wyoming are hydraulically connected with sources of mountain precipitation. The recharge that infiltrates alluvial materials and bedrock outcrops that border the mountain ranges (mountain front recharge), and the thick alluvial deposits underlying stream channels that receive a large proportion of their flows from mountain discharges is especially valuable. Recharge storage in Wyoming builds as snowpack accumulation during late fall, winter, and early spring when seasonal precipitation is higher and cool daily mean temperatures prevent melting. Recharge rates are highest in late spring and the earliest part of summer during and following snowmelt. During those times, vegetation is still in a quasi-dormant state, rates of evapotranspiration are relatively low, and soils have newly thawed. The melting snowpack maximizes contact with the ground surface and enhances the duration and rate of infiltration.

Conversely, the environmental conditions that exist in the semi-arid basin interiors limit the amount and delivery of recharge. There, evapotranspiration rates frequently exceed the low rates of precipitation. During most years, basin recharge events are limited to infrequent rainfalls, usually in the form of high intensity thunderstorms and springtime melting of the relatively thin prairie snowpack. The reduced permeabilities of basin soils, lower permeability and less efficient recharge across horizontal stratigraphic units, and the high efficiency with which semi-arid types of vegetation can utilize sporadic precipitation further restrict the amount of water available for recharge.

During a precipitation event, some of the moisture is intercepted by vegetation before it reaches the ground surface. This water, called canopy storage, is retained briefly and will later be lost to evaporation or fall to the ground. Precipitation that reaches the surface will infiltrate into the ground if the infiltration capacity of the soil has not been exceeded. Initially, infiltrating water will replace any depletion in soil moisture, and then the remaining infiltrating water will percolate downward under the force of gravity through the unsaturated zone to the water table. The hydraulic characteristics and antecedent moisture conditions of the unsaturated zone affect the amount and speed of the infiltrating water that reaches the water table. If the infiltration capacity of the soil is exceeded, water flows overland to be stored on the surface in puddles (depression storage) or to discharge to streams. In the latter case, some of the overland flow may infiltrate the streambed and enter the receiving aquifer as recharge, downstream from the site of precipitation. A general

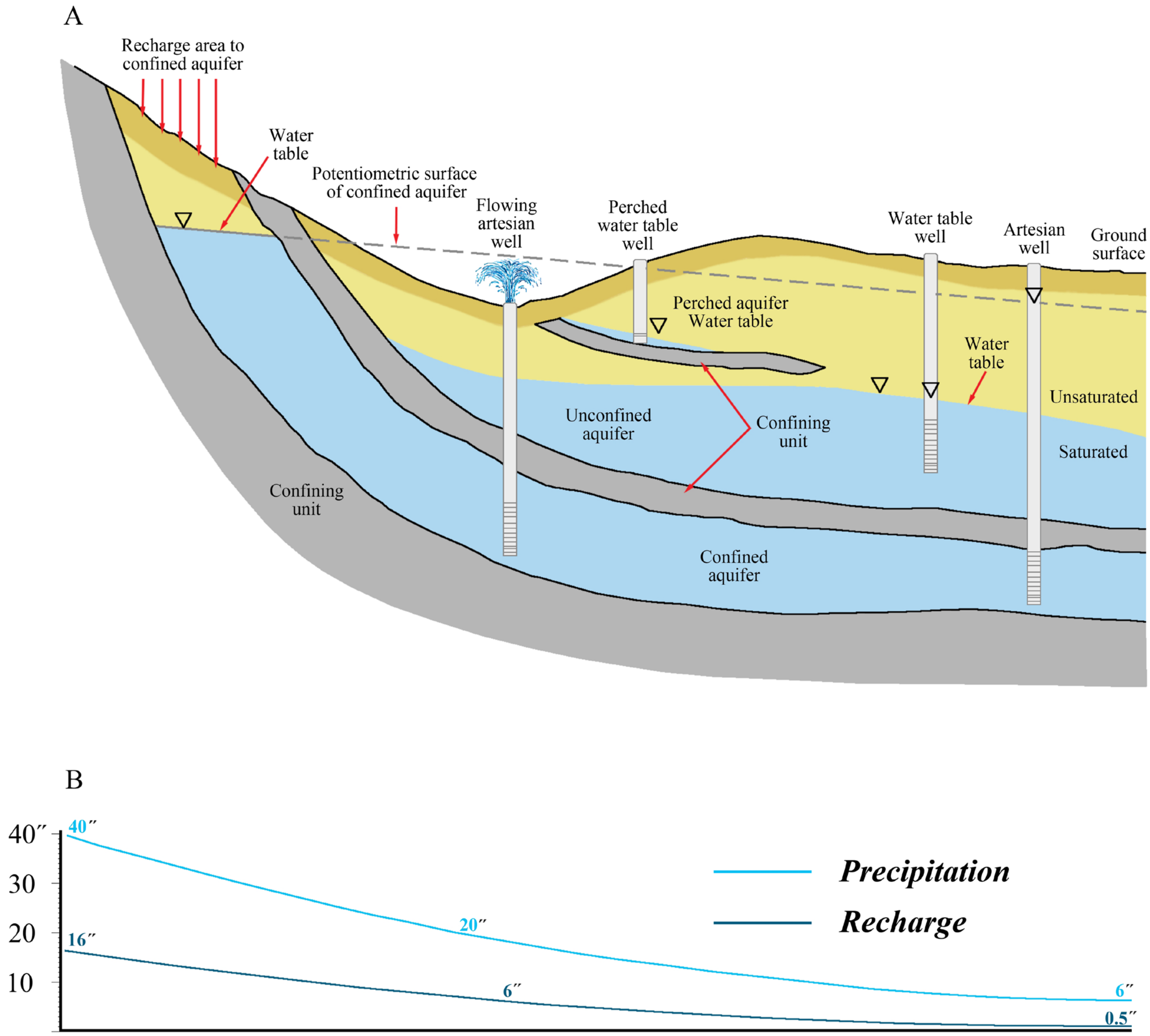

Figure 5-1. Conceptual cross-section of typical groundwater features that occur in Rocky Mountain structural basins and synclinal features. Older hydrogeologic units outcrop and recharge at margins, dip steeply (basinward), and become confined within short distances. Potentiometric surfaces for unconfined aquifers are marked with inverted triangles (▽) (water tables) and as a dashed line extending down-dip where the principal aquifer becomes confined. A perched aquifer has formed above a discontinuous confining unit. The figure shows water table wells completed in unconfined aquifers, and flowing and non-flowing artesian wells completed in the confined aquifer. B. Idealized recharge profile, in inches, basin margin to basin center. Adapted from WWC Engineering and others, 2007.

assumption is that approximately 10 percent of precipitation recharges groundwater.

The description given above is a general simplification of the infiltration process. It should be understood that infiltration rates can vary widely and are affected by multiple factors:

- Depth, composition, and hydraulic properties of the surficial materials (soil, bedrock and paving);
- Depth and degree of bedrock weathering;
- Antecedent soil moisture: was the soil dry, moist or wet before the event;
- Type, abundance, and density of vegetation;
- Extent, density, and proximity of root zones;
- Type, rate, and duration of precipitation;
- Evapotranspiration (ET) rates;
- Slope and aspect of the ground surface;
- Aperture, depth, interconnection, orientation, density, and exposure of bedrock fractures;
- Large openings, both natural (karst, animal burrows) and man-made (mines, pits, well-bores);
- Geospatial distribution, capacity, and permeability of surface depressions;
- Opportunity for recharge from surface waters; and
- Local land use (irrigation, soil stripping, paved areas).

In addition to infiltration from the surface, an aquifer may also receive recharge as leakage from adjacent confining units. Although recharge may flow very slowly from confining unit to receiving aquifer, the volume of leakage can be quite substantial over time provided the geospatial contact area between the two units is large.

Artificial recharge from surface water diversion projects such as reservoirs, irrigation canals, and unlined pits, injection wells, and flow between aquifers in poorly completed wells may be significant in local areas of the Snake/Salt River Basin. The extent of artificial recharge is difficult to evaluate on a regional basis, but might be determined for small watersheds.

While several methods have been described for estimating recharge (Healy and Scanlon, 2010), direct measurement of recharge is problematic due to the high degree of geospatial and temporal variability of precipitation and the numerous factors that affect infiltration. In 1998, the Spatial Data and Visualization Center (SDVC) at the University of Wyoming conducted a statewide recharge evaluation using geospatial analysis. The SDVC published the results in the *Wyoming Groundwater Vulnerability Assessment Handbook* (Hamerlinck and Arneson, 1998). Originally, the SDVC calculated average annual recharge for the 1961 – 1990 period of record by:

- Compiling a map of soil-management-unit boundaries with assigned recharge fraction values (R/P = Average annual recharge / Average annual precipitation), as percentages of precipitation that reaches the uppermost aquifer in a given environment;
- Combining similar geologic units; and
- Overlaying the average annual precipitation map and multiplying recharge fraction by precipitation to calculate average annual recharge.

Hamerlinck and Arneson (1998) observed several general relationships in the scientific literature on recharge:

- Recharge fraction (R/P):
    - o increases as the depth to the water table decreases,
    - o increases as precipitation increases,
    - o increases as the sand content of the soil increases, and
    - o is higher in an above-average precipitation year and lower when precipitation is below average.
- Seasonal patterns and the timing of major events like spring snowmelt alter the fraction of mean annual precipitation that recharges groundwater.

This study used the SDVC approach (Hamerlinck and Arneson, 1998) to estimate average annual recharge in the Wyoming portion of the Snake/ Salt River Basin (**chapter 6**) for the 30-year period of record from 1981- 2010. The analysis used two geospatial datasets: 1) percolation percentages for documented soil/vegetation combinations (**fig. 6-5**) published in the Hamerlinck and Arneson (1998) study, and 2) average annual precipitation (**fig. 3-3**) from 1981 through 2010 (PRISM, 2013). **Figure 5-2** shows average annual recharge for the 1981 – 2010 period of record; this information is summarized in **tables 6-1 – 6-3**.

5.1.3.2 Groundwater discharge

Natural discharges of groundwater occur in many ways. In Wyoming basins, the most common modes of discharge include leakage between geologic units; flow from springs;, subsurface seepage (baseflow) into streams, wetlands, lakes, and other surface waters, and direct evaporation where the water table is shallow enough that capillarity or plant transpiration brings groundwater to the surface (evapotranspiration). Like recharge, the magnitude of total natural discharge is difficult to determine, especially on a basin-wide basis. While some forms of discharge, such as visible surface flows from springs, are readily measured, others are difficult to quantify because they are concealed (leakage between geologic units, subsurface flows in streambeds--i.e., hyporheic flows--or seepage into surface waters) or occur with wide variability over large areas (evapotranspiration). Discharges that cannot be measured directly must be estimated through proxy calculations. For example, using a mass balance (water balance) model can refine estimates when information on recharge and some discharges (e.g., surface water outflow, evapotranspiration) is available, as is the case in this study (**chapter 8**).

In addition to withdrawals from wells, artificial avenues of groundwater discharge include seepage into mines and other excavations, discharges into irrigation and drainage canals, and flow between aquifers in poorly completed wells. Groundwater withdrawals for beneficial use are estimated in the previous water plan (Sunrise Engineering, 2003) and are discussed in **chapter 8**.

Groundwater discharge, buffered by the storage function of an aquifer, is generally more efficient than recharge. While recharge occurs intermittently by percolation through unsaturated materials, discharge is a more continuous process that occurs under more efficient saturated flow conditions. Under natural conditions, where there is no extraction of groundwater, recharge and discharge will reach a state of dynamic equilibrium over a time period that depends on precipitation, hydrogeologic characteristics, aquifer size, and the variability of the particular hydrologic inputs and outputs within the basin in question. Reasonable estimates of both recharge and discharge provide valuable baseline data to evaluate the sustainability of any groundwater development project.

5.1.3.3 Groundwater flow

Gravity drives groundwater flow. After water enters an aquifer in a recharge area it flows under saturated conditions to discharge areas controlled by the hydrogeologic characteristics of the aquifer. The rate of groundwater flow (as volume per unit of time) is determined by the hydraulic conductivity (the velocity with which water can move through the pore space), the cross-sectional area, and the gradient that prevails along the flow path. The time it takes for water to circulate through an aquifer can range from a few days in a shallow, permeable aquifer, to thousands of years in deeper aquifers. The arrangement of aquifers and confining units that store and convey groundwater constitutes the structural framework of the hydrogeologic system within a basin.

Although groundwater flow is driven by gravity, water does not always flow downward, but from areas of higher hydraulic pressure to areas of lower hydraulic pressure. In the deeper subsurface, groundwater can flow from a lower to a higher elevation, as observed at artesian wells (**fig. 5-1**) and some springs that discharge groundwater from deep aquifers. Groundwater will flow in the directions indicated on potentiometric surface maps if permeable pathways exist; however, flow along preferential pathways (e.g., fractures and faults) can depart from the direction of maximum gradient. Hydraulic gradients are commonly steep in low permeability geologic units where there is substantial resistance (friction) to flow. Conversely, high-permeability units, where friction is low, generally exhibit low hydraulic gradients. The slope (gradient) of a potentiometric surface within a highly permeable aquifer is somewhat analogous to a standing body of water, such as a pond where the resistance to flow in any direction is negligible and the gradient is virtually flat.

Groundwater flow rates through aquifers and confining units range from very high to very low, to essentially no-flow. The flow rate through the pores of a highly permeable aquifer of well-sorted gravel or through the large open conduits in a carbonate aquifer may be several feet per second (fps), whereas the flow rate within a clay-rich unit with very low, to essentially no permeability may be less than a few inches every 10,000 years. Hydraulic conductivity varies over 13 orders of magnitude in differing types of hydrogeologic units. Folding, fracturing, and faulting modify the permeability and other hydraulic properties of both aquifers and confining units, generally increasing permeability and decreasing the capacity of confining units to function as barriers to groundwater flow.

Groundwater occurs under unconfined (water table) conditions in unconsolidated deposits and bedrock formation outcrop areas throughout the Snake/Salt River Basin. In shallow, unconfined aquifers, recharge, flow, and discharge are predominantly controlled by topography, vegetation and stream drainage patterns. The water table of an unconfined aquifer is recharged by precipitation and generally reflects the overlying topography especially in areas of high relief. Groundwater from unconfined aquifers can discharge to the surface at springs where the elevation of the water table is greater than the surface elevation. Complex interactions can occur among bedrock aquifers, unconsolidated aquifers, and surface waters, especially along drainages lined with alluvial deposits. The discharge of groundwater to surface drainages contributes to base flow and in some cases constitutes all base flow.

Recharge of the deeper aquifers in the Snake/Salt River Basin occurs primarily in areas where they have been up-folded, eroded, and now crop out in the higher-elevation areas around the perimeter of the basin. These aquifers are unconfined at the outcrop areas, but as groundwater flows downdip from the recharge areas into the basin, it becomes confined by overlying low-permeability strata such as shale and claystone bounding the more permeable aquifers of sandstone, coal, fractured limestone and dolomite. Some recharge to deeper aquifers occurs as leakage from adjacent, usually underlying, hydrogeologic units. Groundwater discharges from confined aquifers to the surface can occur under several conditions. Contact springs discharge where recharge is rejected from fully saturated aquifers into headwater streams at the point where a streambed intersects the surface between a confining unit and an underlying aquifer. Springs also form where joints, fractures, or faults through a confining unit permit flow from an underlying aquifer to reach ground surface. Artesian wells will flow when the pressure head in the confined aquifer is higher than atmospheric pressure at land surface.

Confined groundwater flow within the deeper bedrock formations of the Snake/Salt River Basin is primarily controlled by structure and stratigraphy. Major aquifers and aquifer systems in the Snake/Salt River Basin occur predominantly within interstratified sequences of high- and low-permeability sedimentary strata. The aquifers are commonly heterogeneous and anisotropic on both local and regional scales. Deeper groundwater flow in the Snake/Salt River Basin is predominantly through permeable formations down-gradient from higher to lower hydraulic pressure. Where vertical permeable pathways exist, groundwater will follow them upward toward areas of lower hydraulic pressure.

5.1.4 Groundwater storage, safe yield, and sustainable development

In addition to functioning as the conveyance system for groundwater flow, the saturated geologic units that compose the aquifers of the Snake/Salt River Basin also store enormous volumes of groundwater. Understanding groundwater storage and how to develop groundwater resources in a particular area of interest without depleting storage and natural discharges to unacceptable levels are considered in most development projects. In this section, the basic technical concepts of groundwater storage and the environmental aspects of the "safe yield" concept are discussed. In fact, acceptable (or unacceptable) levels of groundwater depletion are frequently defined administratively by state law, court order, international treaty, or interstate agreements.

Two important aspects of groundwater resource assessments on any scale are the evaluation of both the total volume of groundwater present in an aquifer and the fraction of that volume that can be accessed, developed at an acceptable cost, and used beneficially. Technical, financial, and legal factors determine what fraction of the total volume of groundwater stored within a particular aquifer can be considered an available resource. Initially, development costs, water rights considerations, and water quality requirements are three primary factors that are evaluated to determine what part of the groundwater contained within an aquifer will be producible. The depth to the resource and other physical, cultural, legal, and institutional constraints of the project under consideration may limit accessibility and preclude the development of a particular groundwater resource due to associated costs or technical limitations. Groundwater must be of suitable quality to satisfy the requirements for its intended use. Groundwater quality is addressed in **section 5.5** and **chapter 7**.

The amount of water that an aquifer will yield to natural drainage or to pumping is determined by its hydraulic properties, which are directly or indirectly dependent on an aquifer's effective porosity **(section 5.1.1)**. Important hydraulic properties with respect to the sustainable development of groundwater resources are related to the storage coefficient of the material that composes an aquifer, particularly specific yield for unconfined aquifers and specific storage for confined units.

5.1.4.1 Groundwater storage

The concept of storage coefficient can be applied to both unconfined and confined aquifers. The storage coefficient is the amount of water that a unit volume of an aquifer will release from (or take into) storage per unit change in hydraulic head, expressed as a percentage or decimal fraction.

Specific yield applies only to unconfined aquifers; it is the fraction of water that a saturated unit volume of rock will yield by gravity drainage. Specific yield is expressed as a percent (or decimal fraction) of the unit volume. In an unconfined aquifer, specific yield is essentially the same as effective porosity. Specific retention, also expressed as a percent (or decimal fraction) of the unit volume, is the volume of water that remains in the unit volume of rock after drainage, in isolated pores and attached to the aquifer matrix by molecular attraction and surface tension (capillarity). Because capillarity is higher in fine-grained materials which have smaller pore size and proportionately greater pore-surface area, it follows that finer-grained aquifers in general have higher specific retentions than coarser-grained aquifers even though finer-grained materials may have higher total porosity than coarser-grained materials. For example, a larger fraction of the total water would be retained after drainage in a cubic foot of fine sand than in a cubic foot of river cobbles. The sum of specific retention and specific yield is equal to porosity. Highly productive unconfined aquifers are characterized by high specific yields.

The mechanisms of releasing groundwater from unconfined and confined aquifers are very different. In an unconfined aquifer, water is simply drained by gravity and hydraulic head is lowered. In a confined aquifer, water released from storage comes from the expansion of groundwater and the compression of the rock matrix as water pressure is reduced by pumping or artesian discharge. This is called the specific storage. Because the volume of water that is produced due to these elastic properties (specific storage) is negligible in an unconfined aquifer, the storage coefficient in an unconfined aquifer is essentially equal to specific yield. Conversely, specific yield cannot be determined for a confined aquifer unless the water level (hydraulic head) is reduced to the point that the aquifer becomes unconfined, after which the storage coefficient is essentially equal to the specific yield.

To some extent, the groundwater stored in an aquifer can operate as a buffer between recharge, natural discharge and withdrawals, allowing relatively constant production of groundwater during periods of variable recharge. Enormous volumes of water can be released from storage in a geospatially large aquifer from relatively small persistent declines in hydraulic head, allowing continual withdrawal through periods of deficient recharge. Large declines in hydraulic head from over pumping, however, can reduce aquifer water levels to the point where recharge is induced, turning gaining streams into losing streams or drying up spring flows. Because of the difference in how water is released from storage, specific yields in unconfined aquifers are generally orders of magnitude larger than the specific storage of confined aquifers. Thus, unconfined aquifers yield substantially more water per unit decline in hydraulic head over a much smaller area than do confined aquifers. Unconfined aquifers are therefore generally more attractive prospects for development. Properly managed, groundwater is one of society's most important renewable resources; however, over-pumping can result in a long-term and perhaps irreversible loss of sustainability through storage depletion and compression of the aquifer material.

5.1.4.2 Safe yield

The term "safe yield" is used to describe the rate of groundwater production that can be sustained without causing an unacceptable level of depletion of storage volume or other adversities, such as degradation of groundwater quality or depletion of surface water flows. In the past, safe yield estimates were tied to average annual recharge rates and were thought to predict aquifer responses to long-term withdrawals and recharge inflows. Safe yield estimates have been applied over a wide range of scale, from individual wells to entire structural or drainage basins. The concept of safe yield originated in the early twentieth century with engineering studies of surface water reservoirs.

The concept was subsequently applied to groundwater resources. Lee (1915), in his article, *The Determination of Safe Yield of Underground Reservoirs of the Closed Basin Type*, first described safe yield as, "the limit to quantity of water that can be withdrawn regularly and permanently without dangerous depletion of the storage reserve." Lee noted that safe yield… "is less than indicated by the rate of recharge, the quantity depending on the extent to which soil evaporation and transpiration can be eliminated from the region of groundwater outlet." Meinzer (1923) placed it within the context of economics when he defined safe yield as ". . . the rate at which ground water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible." However, it is now recognized that ownership, legal, financial and environmental issues, the potential for aquifer damage, and interference with the development of other resources must also be considered in evaluating "safe yield" for groundwater development. The definition given by Fetter (2001) includes these factors,

> "The amount of naturally occurring groundwater that can be economically and legally withdrawn from an aquifer on a sustained basis without impairing the native groundwater quality or creating an undesirable effect such as environmental damage. It cannot exceed the increase in recharge or leakage from adjacent strata plus the reduction in discharge, which is due to the decline in head by pumping."

Two notable misconceptions that arose in early discussions of the safe yield concept persist to this day. The first is that groundwater withdrawals from wells and springs are sustainable as long as they do not exceed the amount of annual recharge in a particular area. A second, persistent belief follows from the first; developing a water budget will determine a "safe" amount of groundwater development.

Theis (1940) concisely addressed the misconception relating safe yield to annual recharge levels by identifying the sources of water for groundwater development,

> "…under natural conditions…previous to development by wells, aquifers are in a state of approximate dynamic equilibrium. Discharge by wells is thus a new discharge superimposed upon a previously stable system and it must be balanced by an increase in the recharge of the aquifer, or by a decrease in the old natural discharge or by loss of storage or by a combination of these."

The scientific literature has continually supported Theis' observations since then. In brief, the amounts of groundwater withdrawn by new development projects initially come from storage depletions and then gradually transition to induced recharge of surface water (stream flow depletions). In the best case, the newly developed groundwater system will reach a new state of dynamic equilibrium over time but this includes, by necessity, depletions of streamflow or groundwater storage or both. Thorough explanations of these concepts can be found in Sophocleous (1998) and Barlow and Leake (2012).

In the past, when it was thought that the upper limit of an aquifer's safe yield was determined by the amount of annual recharge, the sustainability of groundwater development was frequently analyzed by a conservation of mass approach variously referred to as a water balance, hydrologic budget, or water budget. The fundamental expression for this type of analysis as applied to groundwater resources is:

Recharge – Discharge = Change in Storage
(measured over the same time period)

By application of this equation, recharge rates could be estimated by making reasonable estimates of natural discharges and groundwater withdrawals from wells if it is assumed that there was to be no change in storage. The recharge estimates were then used to determine the upper limit of an aquifer's safe yield.

Average annual recharge rates for the Snake/Salt River Basin estimated by the SDVC (Hamerlinck and Arneson, 1998), are presented in **figure 5-2**. Based on the SDVC evaluation, annual recharge to specific groups of aquifers is estimated and discussed in **section 6.2**. A water balance for the Snake/Salt River Basin was prepared for this study (**chapter 8**) using information provided in the previous Snake/Salt River Basin Water Plan (Sunrise Engineering, 2003) and additional information developed by the WSGS. The aquifer-specific recharge estimates contained in **chapter 6** of this study were integrated into the water balance which should be used to:

- Provide a comparison of estimated groundwater withdrawals to estimated levels of natural discharge and recharge;
- Emphasize the mass balance aspect of water resources that is, "water in" (recharge) equals "water out" (natural discharges and artificial withdrawals);
- Develop further understanding of the groundwater/surface water system of the basin, and;
- Stimulate discussion among stakeholders of what constitutes sustainable yield (**section 5.1.4.3**) in the Snake/Salt River Basin.

Practically, it is unlikely that a unique and constant value of safe yield can be calculated accurately on the basin scale because of a number of limiting physical and temporal factors.

- Drainage basins cannot be treated as homogeneous underground reservoirs but are complex systems of aquifers and confining units that possess, instead, high levels of geological and hydrological heterogeneity. For example, a large drainage basin such as the Platte River (Taucher and others, 2013), may contain several structural basins, wholly or in part. Because of these complexities, the understanding of key factors such as basin geometry and structure, hydraulic relationships between basin hydrogeological units, and deep basin hydrodynamics is largely absent within a regional model.

- Aspect(s) of spatial scale must be considered. An analysis of total groundwater uses over a regional scale, such as a river basin, may indicate that groundwater withdrawals constitute a small percentage of calculated annual recharge and imply that water resources are not over-utilized. A regional analysis may, however, conceal local scale groundwater storage depletions that have become problematic. Again, in the case of the Platte River Basin (Taucher and others, 2013), a basin wide water balance determined that recent annual consumptive uses of groundwater constitute about 13 percent of mean annual recharge. From this analysis, a safe yield evaluation would conclude that groundwater storage levels in the basin are relatively secure. In fact; some areas of the High Plains aquifer in Laramie County have seen maximum water level declines of 25-50 feet since 1950 (McGuire, 2013).

- Sufficient datasets required to make such estimations have not been obtained in most drainage basins for a number of reasons. First is the expense of collecting adequate hydrogeologic data from an acceptably sized sample set. The problem is further exacerbated in lightly populated rural areas where groundwater wells are sparsely distributed. There, adjacent sampling points (wells) are frequently separated by miles of unpaved roads, inaccessible during winter and early spring months. Second, wells are most likely sited in hydrogeologic units where the probability of successful completion is highest. Thus the available hydrogeologic data is skewed toward over-represented productive areas and away from less productive units where few wells are drilled. For example, 65 percent of likely producing wells of all types are sited on Quaternary Alluvial units which comprise 20% of basin surface area (**table 6-3**). The remaining wells (35 percent) are sited in bedrock aquifers (**figs. 8-1** through **8-4**).

- Hydrologic inputs (recharge) and outputs (discharges) are not delivered instantaneously and, in most cases, have not been accurately measured. Similarly, changes in storage are dependent on aquifer response times that can range from days to hundreds of years (Sophocleous, 2005). Thus, currently observed changes in storage may reflect present day discharges superimposed on recharge levels from decades past. In such cases, water managers must be careful to avoid evaluating current aquifer storage volumes relative to recent precipitation rates given the long lag times of some aquifers and the cyclic nature of drought in the semi-arid west.

5.1.4.3 Sustainable development

The concept of sustainable development has received increasing attention in the international water resources community since it first appeared in the early 1980s. The World Commission on Environment and Development defined sustainable development as, "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs." In the U.S., sustainable development of water resources continues to grow in importance in light of USGS studies documenting widespread groundwater storage declines in the U.S. (Konikow, 2013; Bartolino and Cunningham, 2003) and the related effects of surface water depletion and land subsidence (Galloway and Burbey, 2011), most notably in the arid and semi-arid western states.

The American Society of Civil Engineers (ASCE, 1998) define sustainable water systems as, "… those designed and managed to fully contribute

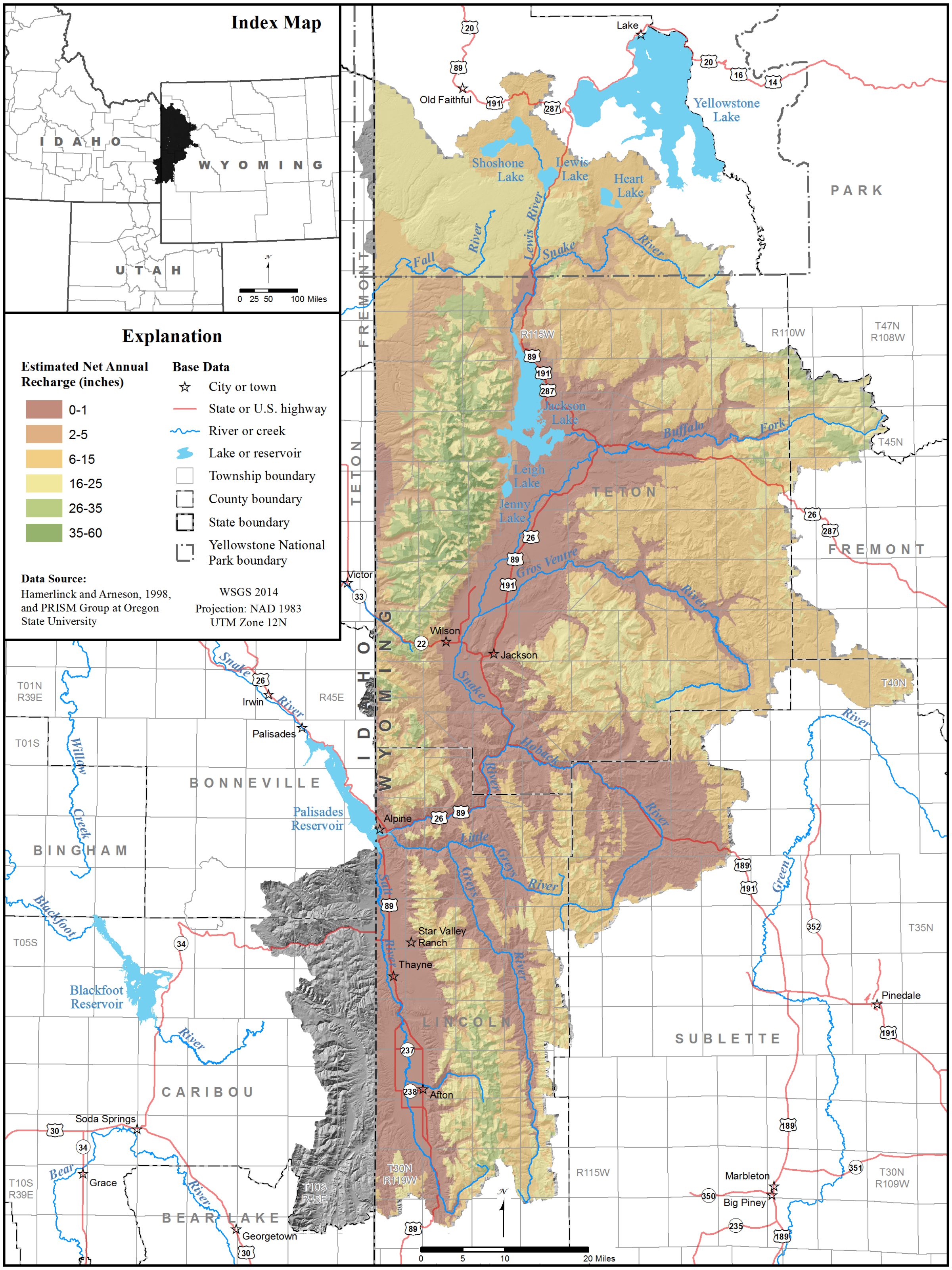

Figure 5-2. Estimated net annual aquifer recharge, in inches, Snake/Salt River Basin, Wyoming.

to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity." The list of factors that affect the planning and development objectives of any water resource system is extensive. Water planners are required to consider current and future water demands, population, land use, climate, public opinion, water resource utilization, technology, and hydrologic science. Given the uncertainties encountered in these analyses, it is likely that no constant single value of sustainable yield can be developed for a particular project. The determination of sustainable yield is not a single set of calculations but a process that will require periodic reevaluation as the design elements change with time (Maimone, 2004).

Sophocleous (1998) describes a six step procedure first proposed by Mandel and Shiftan (1981) to estimate the sustainable yield of an aquifer:

1. Determine mean annual recharge.
2. Identify the first unacceptable affect that will occur as water levels are lowered. This may be defined as a physical constraint (depletion of measured springflow), or a violation of government regulations (infringement on senior water rights, mandated in-stream flows, or provisions of an interstate compact).
3. Define the quantitative relationship between water levels and the timing and extent of the unacceptable affect previously identified. This step may use widely known mathematical functions or the development of groundwater models that apply over wide areas of the aquifer or to a few critical locations only.
4. Determine minimal acceptable water levels for the aquifer or for the critical areas of interest.
5. Calculate the rate of natural discharge that will result when a new state of dynamic equilibrium consistent with the minimal water levels is established.
6. The sustained yield is the difference between Steps 1 and 5.

To this, a seventh step might be added, *"Review and reevaluate yield estimates as water demands, population, land use, climate, public opinion, water resource utilization, technology, hydrologic understanding of the system, and available alternate water sources change with time."*

The concept of *sustainable development* recognizes the ultimate sources of groundwater withdrawals defines the first unacceptable effect(s) of storage and surface flow depletions, establishes minimal water levels that ensue from those depletions and calculates the rate of diminished natural discharge. Still, if integrated into any groundwater development program, the results of sustainable yield calculations must be supported by a long term monitoring plan that utilizes an adaptive management approach. Barlow and Leake (2012) discuss, in depth, the challenges of designing, conducting, and analyzing the results of a streamflow depletion monitoring program.

5.2 Map/rock units: geologic, stratigraphic, and hydrogeologic

The geologic framework for the Available Groundwater Determination Technical Memorandum for the Snake/Salt River Basin is the assemblage of rocks and other geologic elements that compose the groundwater basins, their hydrologic properties, and the stratigraphic and structural interrelationships that provide the plumbing system for the recharge, storage, and flow of groundwater. Geologic units and rock units are distinct, mappable units (described in **appendix A** and discussed further in **chapter 7**) that have been defined and described in the geologic nomenclature. They are classified in descending order of magnitude as supergroups, groups, formations, members, beds, tongues, and flows.

The North American Stratigraphic Code (2005) establishes the basis for the definition, classification, and naming (nomenclature) of distinct and mappable bodies of rock. These bodies are referred to as geologic units and rock units. While the code does not clearly distinguish between the two, rock units are commonly considered equivalent to lithostratigraphic units, defined by mappability, stratigraphic position, and lithologic consistency. Geologic units are distinguished over a wider range of properties, such as lithology, petrography, and paleontology, and can include lithostratigraphic (lithodemic for non-layered intrusive and metamorphic rocks), biostratigraphic, chronostratigraphic, geochronologic, and other less familiar stratigraphic units. Stratigraphic units are generally layered or tabular and established on the basis of any or several of the properties that distinguish them from adjacent geologic units.

The USGS Geologic Map of Wyoming (Love and Christiansen, 1985) provides the most comprehensive and up-to-date map of surface geology readily available and relevant for this study. The map delineates the surface outcrops of distinguishable bodies of "rocks" as "map units." The explanation sheet accompanying the Geologic Map of Wyoming describes where certain map/rock units that consist of one or more stratigraphic units have been combined on the map because of cartographic limitations. The explanation also describes the chronologic and geographic correlations between stratigraphic and map units, and the geographic and chronological distribution of both the map units and their component stratigraphic units. The WSGS "Stratigraphic Chart Showing Phanerozoic Nomenclature for the State of Wyoming" (Love and others, 1993) correlates the stratigraphic units shown on the 1985 map explanation developed from the individual 1° x 2° (1:250,000 scale) geologic quadrangle maps covering the state, and includes revisions subsequent to the 1985 map. Conceptually, because the map/rock units of the Geologic Map of Wyoming may consist of more strictly defined stratigraphic units (primarily lithostratigraphic units), they are considered to be geologic units. The USGS and the WSGS compiled the map/rock units in the 1985 Geologic Map of Wyoming into a digital database of GIS geologic units which was used in the development of **plate 1** (surface geology), **plate 2** (surface hydrogeology), and the hydrostratigraphic chart contained in **plate 5**.

The Snake/Salt River Basin GIS geologic units mapped on **plate 1** are described in **appendix A**. Throughout this study, bodies of rock are described in terms of rock (lithostratigraphic) units where the more restrictive distinction is applicable (primarily in **chapter 7**) and as geologic units where a more inclusive definition is appropriate. **Plate 2** maps the exposures of the hydrogeologic units in the Snake/Salt River Basin. Hydrogeologic units can be composed of multiple, or portions of geologic and/or rock units. The units that compose an aquifer or aquifer system in one area may be considered differently in another area where the same units have different hydrologic properties or are composed of different geologic units. The hydraulic, physical, and hydrogeochemical characteristics of individual hydrogeologic units (aquifers and confining units) established on the hydrostratigraphic chart are discussed in detail in **chapter 7** regarding their component geologic or lithostratigraphic units.

Plates 4, 5, and **6** provide hydrostratigraphic information from previous studies so that informed readers can track the historical development of understanding the basin's hydrostratigraphy. The hydrostratigraphic chart is based on stratigraphic units, several of which are not distinguished within the GIS geologic units used to develop **plate 2**. In addition, GIS geologic units used to map specific hydrogeologic units comprise different stratigraphic units in different areas in the Snake/Salt River Basin. This limitation precluded designating some GIS units as a specific **plate 2** aquifer or confining unit. In cases where specific designations could not be made (some Mesozoic and Paleozoic units), the hydrogeologic units on **plate 2** are categorized as undifferentiated.

Most geologic maps are now constructed using computers. Computerization allows great flexibility in how geologic data can be organized, presented, and updated. The value of this technology is reflected in this technical memorandum and the other studies that compose the State Water Plan. Map data is available to the public in formats that allow a skilled viewer to access, download, and process geospatial data, and work directly with maps and figures presented within this and other reports. Computerization greatly facilitated the process of organizing the GIS geologic units into hydrogeologic units and the construction of the surface hydrogeology map (**pl. 2**) and associated hydrostratigraphic charts. As discussed in **sections 5.1.3.1** and **6.2**, the GIS-based surface hydrogeology map also allowed a reasonable quantitative estimate of annual recharge to the outcrop areas of aquifers exposed in the Snake/Salt River Basin.

5.3 Wyoming statewide aquifer classification system

The 2007 Wyoming Statewide Framework Water Plan (WWC Engineering and others, 2007) proposed a generalized aquifer classification system for the entire state based on the amounts of water a hydrogeologic unit has historically provided for beneficial use. Individual geologic units are assigned to one of seven categories by evaluation of their hydrogeologic characteristics. The statewide classification system distinguishes the following seven hydrogeologic categories:

Major aquifer - alluvial: The highly permeable, unconsolidated, flat-lying sand and gravel deposits that compose the alluvium located along rivers and streams are some of the most productive aquifers in the state and the Snake/Salt River Basin. Under favorable conditions these aquifers can provide well yields of 500-2,000 gallons per minute (gpm). Yields are generally lower where the deposits are either thin, contain abundant fine-grained material, located at higher elevations or hydrologically isolated from active streams (e.g., terrace deposits). Flow through unconsolidated material occurs through primary (intergranular) porosity. Where the alluvial aquifer is hydraulically connected with an active stream, direct infiltration from the stream provides most of the groundwater in storage, and alluvial-aquifer water quality reflects the water quality of the stream, with modification by the mineral composition of the aquifer matrix. Where discharge from shallow bedrock aquifers is a primary source of alluvial-aquifer recharge, surface water quality is similarly influenced.

Major aquifer - sandstone: Consolidated bedrock formations, composed primarily of permeable coarser-grained lithologies, such as sandstone and conglomerate, commonly supply useable quantities of groundwater. In some cases, sandstone aquifers yield large quantities of good quality groundwater. Most of the groundwater stored in these aquifers is held in the sandstones' primary porosity. Porous flow is generally dominant; however, fracture flow can be significant in structurally deformed areas. Within the interior valleys, the sandstone aquifers are mostly horizontal and some are widespread. Relatively thick sandstone sequences that compose the Tertiary Salt Lake aquifer system and the Mesozoic Nugget aquifer are the most productive sandstone aquifers in the Snake/Salt River Basin. Older Mesozoic sandstone aquifers exposed by erosion along the ridges and flanks of the Snake/Salt River Basin highlands commonly dip to the west (**pls. 1** and **2**) and may contain accessible groundwater resources for several miles downdip of the outcrop areas. Groundwater quality tends to decrease with increasing depth. Some sandstone aquifers may exhibit poor yields due to local heterogeneity, high content of fine-grained material, cementation, and lack of fractures. Layers and lenses of sandstone (and coarser lithologies) are generally the most productive intervals. Where sandstone layers are not thick and widespread but rather heterogeneous and discontinuous, wells must penetrate several individual water-bearing strata to provide adequate flow for the intended use.

Major aquifer – limestone: Carbonate formations are composed primarily of Paleozoic and lower Mesozoic limestone or dolomite that occur throughout Wyoming and are present in all seven major river basins. Well production rates are highly variable in limestone aquifers. Localized areas of vigorous groundwater flow and high productivity are present where enhanced secondary permeability has developed along solution-enlarged fractures caused by structural deformation and groundwater circulation. In the Snake/Salt River Basin, these aquifers are exposed primarily along the ridges and flanks (**pl. 2**) of highlands where the upthrown sides of thrust faults have been eroded away to expose carbonate formations. The potential for vigorous recharge and groundwater circulation in Paleozoic carbonate aquifers is highest in outcrops located along flanks of the Salt River, Wyoming, Gros Ventre, and Teton ranges. In Wyoming, examples of major carbonate aquifers include the Madison, Tensleep, and Bighorn formations. Depending on the degree of enhanced permeability, the major limestone aquifers can host accessible groundwater resources for several miles downdip of their outcrop areas. However, they generally are more deeply buried than the overlying sandstone aquifers and access to them becomes progressively difficult as burial depths increase.

Minor aquifer: These consolidated bedrock formations commonly provide groundwater for local use from relatively low-yielding wells (generally 50 gpm or less). Water quality in the minor aquifers varies from good to poor. The minor aquifers are typically thinner, more heterogeneous, have lower yields, and are less laterally extensive than the major aquifers. Similar to other aquifer types, outcrop areas are characterized by generally better circulation and groundwater quality, both of which deteriorate, in many cases, rapidly with depth.

Marginal aquifer: These consolidated bedrock formations host mostly low-yielding wells (1-5 gpm) that may be suitable for domestic or stock use. Sandstone beds are the primary source of groundwater in marginal aquifers, although fractured fine-grained strata and coal seams yield water locally. Marginal aquifers rarely yield substantial quantities of groundwater, and then only under favorable local conditions. The permeability of marginal aquifers is generally low enough that in some areas they also function as minor (leaky) confining units.

Major confining unit: These consolidated bedrock formations are composed primarily of thick layers of marine shale that hydraulically separate underlying and overlying aquifers on a regional scale. These confining shales are some of thickest and most widespread formations in Wyoming. Because of their high clay content, these strata are generally less brittle than other lithologies and therefore less subject to fracturing that could enhance permeability. These units typically yield little or no groundwater, and the groundwater that is produced is commonly of poor quality. Rarely, low-yield wells that produce small quantities of useable groundwater have been completed in isolated zones in confining units. The crystalline Precambrian rocks that underlie the basins and crop out in the surrounding mountain ranges throughout Wyoming are the basal confining unit below the sedimentary basins and the lower limit of groundwater circulation. In and near the upland outcrop areas, these rocks possess enough fracture permeability to sustain springs and low-yield wells that provide good-quality groundwater.

Unclassified: These geologic units are of small extent and lack adequate data for hydrogeologic classification.

The Wyoming Statewide Framework Water Plan (WWC Engineering and others, 2007; fig. 4-9) classified the Snake/Salt River Basin geologic units; the more common names used in the framework water plan for time equivalent stratigraphic units are noted in parentheses:

Major Aquifer - Alluvial

Quaternary alluvium

Major Aquifer – Sandstone

Teewinot and Salt Lake formations
Nugget Sandstone

Major Aquifer - Limestone

Tensleep Sandstone and Minnelusa Formation
Madison Group and Bighorn Dolomite

Minor Aquifer

Quaternary non-alluvial deposits
Twin Creek and Thaynes limestones
Frontier Formation
Phosphoria Formation and related rocks

Marginal Aquifer

Volcanic rocks
Camp Davis, Colter, and Hoback formations
Sohare, Harebell formations
Aspen and Bear River formations
Woodside Shale and Dinwoody Formation

Major Aquitard (Confining Unit)

Cody Shale, Niobrara Formation, Steele Shale, and Baxter Shale

Precambrian rocks

While the 2007 Wyoming Statewide Framework aquifer classification system provides a general summary of the groundwater resources of the seven major drainage basins of Wyoming, the updated individual river basin plans provide a greater level of hydrogeologic detail and analysis. **Plate 2** summarizes the hydrogeology developed by this study for the Snake/Salt River Basin. Correlations between the 2007 Wyoming Statewide Framework Water Plan aquifer classification system (WWC Engineering and others, 2007), and the hydrogeology presented in this study are explained on **plates 4** through **6**.

5.4 Groundwater circulation in the Snake/Salt River Basin

The complex geologic setting of the Snake/Salt River Basin was introduced in **chapter 3** and discussed in detail in **chapter 4**. Unlike other large Wyoming river basins where one regional structural setting dominates, the Snake/Salt River Basin overlies five structural regimes: Thrust Belt structures in the south, the Absaroka and Yellowstone/Snake River Plain volcanic systems to the north, Laramide and later aged uplift structures to the north and east, and Basin and Range Province structure to the west (**chapter 4**; **pl. 1**, and **fig. 4-2** through **4-7**). The following sections discuss groundwater circulation in Quaternary, Thrust Belt, Laramide structural, and volcanic aquifers.

Fault and fracture zones control groundwater circulation in Thrust Belt, Laramide structural, and volcanic aquifers by acting as hydraulic barriers or conduits for groundwater. The effects that a particular set of faults or fractures exerts on groundwater flow can be complex. Numerous physical characteristics of the fault or fracture set, such as its type, spatial extent, deformation type and history, aperture (size of its openings), fluid chemistry and reactions, and orientation, can affect the direction and magnitude of groundwater flows. Other factors that can modify groundwater circulation include the geospatial, hydraulic, and lithologic properties of the rock units that the fault transects and also the fault's proximity, hydraulic connectivity, and spatial relationship to other faults and fracture sets.

Faults most often act as barriers that impede the flow of groundwater across strike in two ways. First, relatively impermeable rocks can be juxtaposed with more permeable units in the adjacent fault wall by the vertical displacement of stratigraphic units. Second, during the formation of the fault, friction between moving fault walls can grind rocks into clay-like, fine-grained, low-permeability sediments. These deposits, called fault gouge, fill in the spaces between the adjacent fault walls forming a fault core that impedes the flow of groundwater. In either case, the flow of groundwater can be redirected either horizontally, along the strike of the fault, or vertically depending on the hydraulic pressure gradients of the surrounding aquifers and confining layers. Many of the springs in the Snake/Salt River Basin occur along normal faults where horizontal groundwater flow has been disrupted and redirected upward to the surface under artesian conditions (**fig. 5-1** and **pl. 3**).

The presence of a fault can also increase the flow of groundwater especially in the damage zones that flank the fault's core. The small faults, fractures, veins, and folds that typically form the damage zones may extend for hundreds of feet on either side of a large fault and can act as groundwater conduits that have hydraulic conductivities which are several orders of magnitude higher than the surrounding host rock. If the damage zones are hydraulically connected to a network of other faults, they can convey water to springs and wells from areas that cover several square miles. The hydrogeologic heterogeneity created by faults can make it difficult to accurately determine the dominant patterns of groundwater circulation in heavily faulted regions, even in areas where numerous monitoring wells exist. This difficulty is exacerbated in many parts of the Snake/Salt

River Basin where bedrock wells are sparse. Thus, groundwater patterns are not well understood in those areas.

5.4.1 Groundwater circulation in Quaternary aquifers (Nolan and Miller, 1995)

In terms of the volume of water withdrawn and the number of wells permitted, the most widely used aquifer system in the Snake/Salt River Basin is the Quaternary alluvial aquifer that lies along the Snake and Salt rivers and their tributaries (Sunrise Engineering, 2003). Nearly all of the basin's irrigation wells (**fig. 8-1**), as well as most of the wells permitted for livestock (**fig. 8-2**), municipal (**fig. 8-3**), and domestic (**fig. 8-4**) uses, are located within the Quaternary system. Nolan and Miller (1995) report that the alluvial aquifer system is recharged primarily by direct infiltration of precipitation, discharge from bedrock aquifers, recharge from irrigation, and infiltration of streamflows in losing reaches of headwater streams. Evapotranspiration, groundwater discharges into surface water flows, and withdrawals from wells constitute the principal forms of aquifer discharge. Groundwater flows within this system generally follow the topography of the watershed drainages, that is, toward or parallel to the channels of the Snake/Salt River and its tributary streams (Nolan and Miller, 1995).

5.4.2 Groundwater circulation in Thrust Belt aquifers (Ahern and others, 1981)

Tertiary, Mesozoic, and Paleozoic bedrock aquifers are exposed on the flanks of the mountain ranges that border the Salt River. The Tertiary aquifer group is extensively utilized and includes the Salt Lake, Wasatch, and Evanston aquifers. Ahern and others (1981) note that groundwater circulation in these aquifers is primarily controlled by local topography and that artesian discharge is common only along stream drainages.

Recharge to these aquifers consists of infiltration of rainfall and snowmelt and streamflow seepage in ephemeral streambed reaches. Natural discharge occurs primarily at gravity-driven springs and seeps (**pl. 3**) and as direct flows into alluvial sediments.

Ahern and others (1981) noted that groundwater circulation in highly fractured, Mesozoic and Paleozoic aquifers is heavily controlled by faults and fracture sets especially in the Salt River drainage, where numerous north-south parallel systems of reverse and normal faults occur (**pl. 1**) typically in relatively close proximity to one another.

5.4.3 Groundwater circulation in Laramide structures (Huntoon 1983a, 1983b, and 1993)

Huntoon (1993) summarized a conceptual model for "The Influence of Laramide Foreland Structure on Modern Groundwater Circulation in Wyoming Artesian Basins" that he and several of his graduate students at the University of Wyoming developed over several years of research and field work, largely within the Bighorn and Platte River basins. Their central thesis is that large-displacement thrust faults, reverse-fault-cored anticlines and associated fractures, and anisotropic permeability that developed during Laramide compressional deformation strongly influence groundwater recharge and circulation through the Paleozoic and lower Mesozoic carbonate aquifers exposed along the major uplifts in Wyoming foreland basins. The main components of this conceptual model include:

- Wyoming foreland mountain ranges consist of large-scale uplifts situated atop large-displacement (thousands of feet) basement thrust faults with fault-severed strata on one side and homoclinal dipping strata on the other.
- The compressional processes that shaped the basins during the Laramide Orogeny also produced smaller structures such as reverse- and thrust-cored asymmetric anticlines within the basins.
- Laramide deformation and erosion established the hydraulic boundaries of

groundwater circulation in Wyoming's structural basins.

- Groundwater circulation is not only controlled by Laramide structures, but also alters their hydrogeology:
  - o Fracture (secondary) permeability within carbonate strata associated with faulting and folding has been enhanced by carbonate dissolution.
  - o Any fracture can potentially enhance permeability, even if formed in a compressional environment (e.g., the trough of a synclinal fold).
  - o Fractures parallel or oblique to the crests of folds, along with bedding-plane partings, formed during anticlinal folding. These fractures are extensional and have maximum potential for developing dissolution-enhanced, highly anisotropic permeability. Where extensional fractures develop, their permeability dominates local groundwater circulation. Groundwater circulation within areas of highly anisotropic fracture permeability along the crests of anticlinal folds is inhibited across the structural trend and tends to converge within the fractures developed parallel or oblique to the folds.
  - o Large-displacement thrust faults and smaller reverse and normal faults can sever an aquifer's hydraulic connection between recharge areas and the deeper basin interior. Separate groundwater circulation systems develop in both the hanging and footwall of major uplift-bounding, large-displacement faults.
  - o Within synclinal folds the rocks are highly compressed, interstitial porosity is destroyed, and fractures are compressed rather than opened.
  - o Faults can act as either conduits or barriers to flow depending on…. (structural regime, diagenetic/ cementation history, connectivity between hydrogeologic units, relationship to other, proximal faults, relationship to inherited—ancestral—structures they overprint, etc.).

- Karst developed along pre-existing fractures within the major carbonate aquifers during erosion and exposure of the recharge areas, and ongoing karstification, have greatly enhanced the permeability of these aquifers around the perimeters of Wyoming's Laramide basins.

- To a lesser extent, paleokarst, developed when the carbonate strata were exposed during Late Mississippian time, has enhanced permeability; however, the paleokarst has largely been filled in with sediments that reduce permeability.

- Intercrystalline permeability in major carbonate aquifers is generally very low.

- Groundwater circulation primarily parallels bedding. Vertical circulation within the deep, artesian basins is very limited except along faulted and fractured anticlines where the permeability of confining units is enhanced.

- Brittle strata (sandstone, limestone, and dolomite) are more prone to fracture during deformation than fine-grained strata (shale, claystone, and mudstone). Fine-grained strata are also more ductile, and small fractures within these units tend to close and seal under compaction.

- Artesian pressure within the basins increases with depth as the recharge areas of deeper, carbonate aquifers are exposed at generally higher elevations in surrounding mountain ranges.

- Large production from major carbonate aquifers is limited to local areas of large solution-enhanced permeability (modern karstification) developed within and down gradient of recharge areas along homoclinal (not fault-severed) flanks of the Laramide uplifts where these aquifers are exposed. How far conditions favorable for large yields of acceptable-quality water extend into the basins depends on the trend and continuity of the controlling structure. Large anticlines trending normal or slightly oblique to the perimeter of the basin will generally provide the greatest recharge to the deeper basin and the best opportunities for high-yield wells.

- Although homoclinal margins exhibit hydraulic and stratigraphic continuity, areas that lack subsidiary structures and associated fracturing of the carbonate aquifers have had less opportunity to develop solution-enhanced permeability and therefore accept less recharge. With less groundwater circulation, dissolution-enhanced permeability in recharge areas does not continue into the basins due to diagenetic processes such as compaction, cementation, and recrystallization that destroy porosity and permeability; therefore, transmissivity decreases progressively basinward, and recharge is rejected at springs at the base of the mountains, generally near the location where a significant confining unit covers carbonate aquifers. The difference in diagenetic conditions between recharge areas and the basins increases over time proportional to groundwater circulation (more circulation causes increased dissolution). Nevertheless, homoclinal areas where carbonate aquifers exhibit significant karstification may be favorable groundwater development prospects.

- Groundwater in the major carbonate aquifers at homoclinal basin margins is generally of good quality, and high yields can be obtained under the right conditions.

- In areas where recharge is rejected, surface and groundwater are interconnected.

- Updip areas of the exposed carbonate aquifers may be only partially or intermittently saturated, and the greater topographic relief of the outcrop areas may limit access to optimal drilling locations (tops of anticlines, adjacent to faults).

- The characteristics that make local exposures of the carbonate aquifers optimal for recharge (good exposures, fracture permeability) also make them highly vulnerable to contamination.

- Synclines and the footwall sides of fault-severed aquifers are not good prospects for groundwater development.

- Computer models of the major carbonate aquifers (and petroleum reservoirs) in foreland basins must account for the highly anisotropic trends of permeability and transmissivity to accurately predict yield, drawdown, and other production characteristics.

The conceptual model, described above has obvious implications for groundwater exploration and development, and these concepts have facilitated the successful completion of groundwater development projects throughout the state. Clearly, identifying and mapping structures in targeted groundwater prospects is an important aspect of any groundwater exploration project including those within the Snake/Salt River Basin. Groundwater circulation in the major aquifer systems of the Snake/Salt River Basin is discussed further in **chapter 7**. Several of the components of the conceptual model described above are illustrated in **figure 5-1**.

5.4.4 Groundwater circulation in volcanic aquifers (Cox, 1973)

Volcanic aquifers constitute the most areally extensive, bedrock aquifer exposures in the portion of the Snake/Salt River Basin confined within the boundaries of Yellowstone National Park (**pl.**

1). Extensive volcanic exposures are found also in northeastern and northwestern Teton County and in northwestern Fremont County. With the exception of northwestern Teton County, few wells are completed in volcanic aquifers (**figs. 8-1** through **8-7**) because most volcanic units outcrop within wilderness areas. Volcanic units, composed primarily of basalt and rhyolite flows, tuffs, reworked volcaniclastic material, and igneous intrusions (**chapter 4**), were deposited during two episodes of volcanism. The Eocene volcanic period that occurred between 35 to 53 million years ago (Ma) formed the Absaroka Volcanic Province, now located in the northeastern Snake River Basin. A more recent (0.6 Ma to 16 Ma) volcanic period created the Yellowstone Plateau.

Cox (1973) noted that brecciated zones at the contacts of individual extrusive flows, heavily fractured units and volcanic rocks with high levels of well-connected vesicular porosity, exhibit the most vigorous groundwater circulation and are capable of discharging "a few tens of gallons per minute." Wells and springs in volcanic aquifers that lack these features generally yield "only a few gallons per minute." Natural recharge to volcanic aquifers consists of infiltration by precipitation and snowmelt, streamflow seepage in ephemeral streambed reaches, and inflows from adjacent aquifers. Natural discharges occur at gravity driven springs and seeps (**fig. 7-2**) and as direct flows into alluvial sediments. **Figure 7-2** shows the locations of springs, wells, and associated physical and chemical characteristics within the context of the generalized geology for the Snake/Salt River Basin in Wyoming and tributary areas in Idaho. **Plate 3** lists spring discharge, well yield, and other hydraulic data for nine wells and 46 springs sited in undifferentiated volcanic units. While spring discharges range from 0.8 to 449 gpm, the median value of 3.7 gpm is indicative of the generally low rates of discharge from volcanic aquifers.

5.5 Natural groundwater quality and hydrogeochemistry

The practical availability of a groundwater resource depends on a combination of hydrologic, technical, legal, institutional, and cultural factors. The feasibility of development and potential uses for a groundwater resource primarily depend on water quality. For this study, the USGS compiled groundwater quality data for the Snake/Salt River Basin hydrogeologic units (**section 5.6**) from several sources. These data confirm that the best quality groundwater is generally found in regions closest to recharge areas, and that quality is affected by chemical reactions that occur during infiltration through the vadose zone and circulating through or residing in the aquifer.

Factors that affect groundwater quality include the type and density of vegetation in recharge areas, and the mineral composition, grain size, transmissivity, rate of circulation, and temperature of the vadose zone and aquifer matrix. This generalization is more applicable to the minor and marginal aquifers of the Snake/Salt River Basin than to the major aquifers, within which groundwater circulation is relatively (often substantially) more vigorous. Groundwater quality in the Snake/Salt River Basin varies from fresh water, with total dissolved solids (TDS) less than 1,000 mg/L (ppm) that is suitable for any domestic purpose, to briny, deep, oil field aquifers unsuitable for virtually any use, with TDS greater than 300,000 mg/L.

In the absence of irrigation, most alluvial aquifers receive recharge from hydrologically connected streams and underlying or adjacent bedrock. Irrigation can dominate recharge when application is active. Direct precipitation can also add to recharge but due to high evapotranspiration rates in the interior lowlands, the amount of precipitation that reaches the water table is diminished, sometimes severely. Where recharge from streams dominates, groundwater quality is generally good. Sand, gravel, and other unconsolidated aquifer materials filter sediment, bacteria, and some contaminants from surface waters, producing water that is clear and with a chemical composition that reflects the composition of the source waters. Where bedrock recharge sources dominate alluvial groundwater quality reflects that of the surrounding formations in proportion to their contribution, commonly at a higher TDS concentration than recharge from surface waters.

Irrigation water also affects groundwater quality in proportion to its TDS composition. In addition, irrigation water applied to permeable soil that has not been naturally saturated for millennia will dissolve, mobilize, and concentrate soluble minerals, primarily salts. Irrigation return flows can degrade water quality in streams.

Bedrock aquifers receive recharge through the infiltration of precipitation, by discharge from adjacent bedrock and alluvial formations, and from surface waters, including irrigation. In general, recharge is dominated by precipitation in outcrop areas where there is no natural surface water or irrigation. Recharge from surface water is prevalent along streams and associated saturated alluvial deposits; however, groundwater discharge from bedrock to streams that support baseflow is also common throughout the Snake/Salt River Basin. Recharge of bedrock aquifers from streams is generally restricted to periods of very high flow and flooding. Groundwater developed in bedrock aquifers close to recharge areas or at shallow depth may be of high quality, regardless of the host geologic unit. As water flows deeper into the basins, it generally becomes more mineralized. Calcium-bicarbonate type water is dominant in and near recharge areas, whereas sodium levels generally increase relative to calcium and sulfate, and chloride dominates over bicarbonate, in deeper aquifers. In general, groundwater quality tends to be better in more productive bedrock aquifers because more active groundwater circulation provides less opportunity and time for minerals present in the rock to dissolve.

Section 5.5.1.3 contains descriptions of the methods used to access, screen, and statistically summarize water quality data for this report. Detailed discussion of water quality analyses of samples collected from the Snake/Salt River Basin aquifers and their component geologic and lithostratigraphic units is provided in **chapter 7.**

5.5.1 Groundwater quality

This section describes groundwater quality for the Snake/Salt River Basin. Specifically, this section addresses how data on chemical constituents for the Snake/Salt River Basin groundwater study were accessed, compiled, screened, and statistically summarized.

5.5.1.1 Regulation and Classification of Groundwater

Groundwater quality in Wyoming is regulated by two agencies. The Wyoming Department of Environmental Quality (WDEQ) Water Quality Division (WQD) regulates groundwater quality in Wyoming, and the U.S. Environmental Protection Agency (USEPA) Region 8 Office, headquartered in Denver, regulates the public water systems located within the state. Each agency has established groundwater standards, and revises and updates them periodically.

Groundwaters in Wyoming are classified with respect to water quality in order to apply these standards. The State of Wyoming through the WDEQ/WQD has classified the groundwaters of the State, per *Water Quality Rules and Regulations, Chapter 8 – Quality Standards for Wyoming Groundwaters* (http://deq.state.wy.us/wqd/WQDrules/Chapter_08.pdf), as:

- <u>Class I Groundwater of the State</u> Groundwater that is suitable for domestic use.
- <u>Class II Groundwater of the State</u> – Groundwater that is suitable for agricultural (irrigation) use where soil conditions and other factors are adequate for such use.
- <u>Class III Groundwater of the State</u> Groundwater that is suitable for livestock.
- <u>Class Special (A) Groundwater of the State</u> Groundwater that is suitable for fish and aquatic life.
- <u>Class IV Groundwater of the State</u> Groundwater that is suitable for industry.
- <u>Class IV(A) Groundwater of the State</u> Groundwater that has a total dissolved solids (TDS) concentration not in excess

of 10,000 milligrams per liter (mg/L). This level of groundwater quality in an aquifer is considered by the USEPA under Safe Drinking Water Act (SDWA) provisions as indicating a potential future drinking water source with water treatment.

- Class IV(B) Groundwater of the State Groundwater that has a TDS concentration in excess of 10,000 mg/L.

- Class V Groundwater of the State Groundwater that is closely associated with commercial deposits of hydrocarbons (oil and gas) (Class V, Hydrocarbon Commercial) or other minerals (Class V, Mineral Commercial), or is a geothermal energy resource (Class V, Geothermal).

- Class VI Groundwater of the State Groundwater that may be unusable or unsuitable for use.

5.5.1.2 Standards of groundwater quality

In this report, groundwater quality is described in terms of a water's suitability for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards (WSGS **table 5-2)** and summary statistics for environmental and produced water samples tabulated by hydrogeologic unit as quantile values (**appendices E-1** to **E-6**). In assessing suitability for domestic use (USEPA health-based standards of Maximum Contaminant Levels (MCLs) and Health Advisory Levels (HALs) are used as guides (however, these standards are not legally enforceable for any of the sampling sites used in this study). The USEPA Secondary Maximum Contaminant Levels (SMCLs), which generally are aesthetic standards for domestic use, and WDEQ Class II groundwater standards for agriculture, Class III standards for livestock and Class IV standards for industry are used as guides for assessing suitability.

Many groundwater samples used in this study were not analyzed for every constituent for which a standard exists. In this report, the assessment of suitability of water for a given use is based *only* on the concentrations of constituents determined; the concentration of a constituent not determined could possibly make the water unsuitable for a given use.

Water-quality concentrations are compared to three types of USEPA standards: MCLs, SMCLs, and lifetime HALs. The USEPA MCLs (U.S. Environmental Protection Agency, 2012) are legally enforceable standards that apply to public water systems that provide water for human consumption through at least 15 service connections, or regularly serve at least 25 individuals. The purpose of MCLs is to protect public health by limiting the levels of contaminants in drinking water. The MCLs do not apply to groundwater for livestock, irrigation, or self-supplied domestic use. The MCLs, however, a valuable reference when assessing the suitability of water for these uses.

The USEPA SMCLs (U.S. Environmental Protection Agency, 2012) are non-enforceable guidelines regulating contaminants in drinking water that may cause cosmetic effects (such as skin or tooth discoloration) or have negative aesthetic effects (such as taste, odor, or color) in drinking water. Lifetime HALs are based on concentrations of chemicals in drinking water that are expected to cause any adverse or carcinogenic effect over a lifetime of exposure (U.S. Environmental Protection Agency, 2012) and will be reffered to as HALs in the remainder of the report. Because of health concerns, the USEPA has proposed two drinking-water standards for radon (U.S. Environmental Protection Agency, 1999)— an MCL of 300 picocuries per liter (pCi/L) and an alternative MCL (AMCL) of 4,000 pCi/L for communities with indoor air multimedia-mitigation programs. Radon concentrations herein are compared, and exceedance frequencies calculated, in relation to the formerly proposed MCL of 300 pCi/L and the formerly proposed alternative AMCL of 4,000 pCi/L.

Water-quality standards for Wyoming Class II, Class III, and Class IV groundwater (Wyoming Department of Environmental Quality, 1993) also are used for comparisons in this report. Class II groundwater is water that is suitable for agricultural (irrigation) use where soil conditions and other factors are adequate. Class III groundwater is water that is suitable for livestock watering. Class IV groundwater is water that is suitable for industry. The Class IV TDS standard (10,000 mg/L) also corresponds to the USEPA underground source of drinking water (USDW) TDS standard established as part of underground injection control (UIC) regulations. These Wyoming standards are designed to protect groundwater that meets the criteria of a given class from being degraded by human activity. They are not meant to prevent groundwater that does not meet the standards from being used for a particular use. Like the USEPA standards, they serve only as guides in this report to help assess the suitability of groundwater for various uses.

5.5.1.3 Sources, screening, and selection of data

Groundwater-quality data compiled through 2011 were gathered from the USGS National Water Information System (NWIS) database (http://waterdata.usgs.gov/wy/nwis/qw/), the USGS Produced Waters Database (PWD) (http://energy.cr.usgs.gov/prov/prodwat/), the Wyoming Oil and Gas Conservation Commission (WOGCC) database (http://wogcc.state.wy.us/), the University of Wyoming Water Resources Data System (WRDS) database (http://www.wrds.uwyo.edu/wrds/dbms/hydro/sel.html), and other sources such as consultant reports prepared in relation to development of public water supplies. Methods used to screen data differ among the data sources, but the overall objective of all screening was to identify and remove samples that (1) were duplicates; (2) were not assigned to hydrogeologic units or were assigned to hydrogeologic units that contradicted local geologic information, particularly for shallow wells; (3) had inconsistent water-chemistry information such as poor ion balances or substantially different values of total dissolved solids and the sum of major ions; or (4) were unlikely to represent the water quality of a hydrogeologic unit because of known anthropogenic effects; for example, samples from wells monitoring known or potential point-source contamination sites or mining spoils sites. Groundwater-quality sample locations retained after data screening, and used herein, are shown in **figure 7-1**.

Many of the groundwater sites in the Snake/Salt River Basin had been sampled more than once; however, only one groundwater sample from a given site was selected for this study, to avoid biasing the statistical results in favor of multiple-sample sites. In choosing among multiple samples from a site or well/hydrogeologic-unit combination, either the most recent sample, the sample with the best ion balance, or the sample with the most complete analysis was retained in the final dataset.

Chemical analyses of groundwater-quality samples available from the USGS PWD were included in the dataset used for this report. Produced water is water co-produced with oil and gas. The PWD includes samples within the Snake/Salt River Basin. Only those PWD samples from a wellhead or from a drill-stem test were included in the dataset. Samples that had not been assigned to a hydrogeologic unit were removed from the dataset. The PWD samples were then screened to retain a single sample per well/hydrogeologic-unit combination. Some samples were removed because their water chemistry was identical to that of other samples, indicating probable duplication of sample records. The PWD documentation indicated that samples generally had been screened to remove samples showing an ion balance greater than 15 percent—strictly, an imbalance between anion and cation activity of greater than 15 percent. The PWD generally contains chemical analyses for major ions and TDS. According to PWD documentation, some sample analyses may have reported the sum of sodium and potassium concentrations as sodium concentration alone.

Chemical analyses of groundwater-quality samples available from the WRDS database were included in the dataset used for this report when information was available to identify the hydrogeologic unit, locate the spring or well, and the site was not included in the USGS NWIS database. In addition, WDEQ monitoring wells located at sites of known or potential groundwater contamination were removed from the dataset because the objective of this study is to describe general groundwater quality based on natural conditions. Samples showing an ion balance greater than 10 percent were removed from the WRDS dataset.

Groundwater quality in the Snake/Salt River Basin varies widely, even within a single hydrogeologic unit. Water quality in any given hydrogeologic unit tends to be better near outcrop areas where recharge occurs, and tends to deteriorate as the distance from these outcrop areas increases and (residence time increases). Correspondingly, the water quality in a given hydrogeologic unit generally deteriorates with depth.

Some of the water-quality samples from aquifers in Quaternary- and Tertiary-age hydrogeologic units came from wells and springs that supplied water for livestock and wildlife. Wells that do not produce usable water generally are abandoned, and springs that do not produce usable water typically are not developed. In addition, where a hydrogeologic unit is deeply buried, it generally is not used for water supply if a shallower supply is available. For these reasons, the groundwater-quality samples from aquifers in the Quaternary-, Tertiary-, and some Paleozoic-age hydrogeologic units most likely are biased toward better water quality, and do not represent random samples. Although this possible bias likely does not allow for a complete characterization of the water quality of these hydrogeologic units, it probably allows for a more accurate characterization of the units in areas where they are shallow enough to be used economically.

5.5.1.4 Water quality characteristics

The TDS concentration in groundwater tends to be high with respect to the USEPA SMCL in most of the Snake/Salt River Basin, even in water from shallow wells. This is not surprising, given the arid climate and small rate of recharge in much of the study area. High TDS can adversely affect the taste and odor of drinking water, and a high TDS concentration in irrigation water has a negative effect on crop production. High TDS concentrations also cause scale build-up in pipes and boilers. The USEPA has not set an MCL for TDS; however, the USEPA SMCL for TDS is 500 milligrams per liter (mg/L) (U.S. Environmental Protection Agency, 2012). The TDS concentration is loosely termed salinity. Groundwater samples are classified in this report in accordance with the USGS salinity classification (Heath, 1983), as follows:

Classification	TDS
Fresh	0–999 mg/L
Slightly saline	1,000–2,999 mg/L
Moderately saline	3,000–9,999 mg/L
Very saline	10,000–34,999 mg/L
Briny	more than 34,999 mg/L

The sodium-adsorption ratio (SAR) represents the ratio of sodium ion activity (concentration) to calcium and magnesium ion activities; it is used to predict the degree to which irrigation water enters into cation-exchange reactions in the soil. High SAR values indicate that sodium is replacing adsorbed calcium and magnesium in soil, which damages soil structure and reduces permeability of the soil to water infiltration (Hem, 1985). The SAR is used in conjunction with information about the soil characteristics and irrigation practices in the area being examined. The high SAR of waters in some hydrogeologic units in the Snake/Salt River Basin indicates that these waters may not be suitable for irrigation.

Many groundwater-quality samples included in the dataset for this report contain high concentrations of sulfate, chloride, fluoride, iron, and manganese, with respect to USEPA standards (U.S. Environmental Protection Agency, 2012) and WDEQ groundwater-quality standards (http://deq.state.wy.us/wqd/WQDrules/Chapter_08.pdf).

Sulfate in drinking water can adversely affect the taste and odor of the water, and may cause diarrhea (U.S. Environmental Protection Agency, 2012). The USEPA SMCL for sulfate is 250 mg/L, the WDEQ Class II groundwater (agricultural) standard is 200 mg/L, and the WDEQ Class III groundwater (livestock) standard is 3,000 mg/L.

Table 5-1. Selected groundwater quality standards and advisories.

[MCL, Maximum Contamination Level; AL, Action Level; SMCL, Secondary Maximum Contaminant Level; HAL, Lifetime Health Advisory Level; USEPA, U.S. Environmental Protection Agency; WDEQ, Wyoming Department of Environmental Quality; WQD, Water Quality Division: --, no data; N, nitrogen; mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter; SAR, sodium adsorption ratio; TDS, total dissolved solids]

Physical characteristics and constituents		Groundwater quality standards and advisories					
		Domestic[1]			Agricultural[2] Class II (WDEQ/WQD)	Livestock[2] Class III (WDEQ/WQD)	Industry[2] Class IV (WDEQ/WQD)
		MCL or AL (USEPA)	SMCL (USEPA)	HAL (USEPA)			
Physical characteristics	pH (standard units)	--	6.50–8.50	--	4.5–9.0	6.5–8.5	--
Major ions and related characteristics (mg/L)	chloride (Cl^-)	--	250	--	100	2,000	--
	fluoride (F^-)	4	2	--	--	--	--
	sulfate (SO_4^{2-})	--	250	--	200	3,000	--
	TDS	--	500	--	2,000	5,000	10,000
	SAR (ratio)	--	--	--	8	--	--
Trace elements (µg/L)	aluminum (Al)	--	50–200	--	5,000	5,000	--
	antimony (Sb)	6	--	--	--	--	--
	arsenic (As)	10	--	--	100	200	--
	barium (Ba)	2,000	--	--	--	--	--
	beryllium (Be)	4	--	--	100	--	--
	boron (B)	--	--	6,000	750	5,000	--
	cadmium (Cd)	5	--	--	10	50	--
	chromium (Cr)	100	--	--	100	50	--
	cobalt (Co)	--	--	--	50	1,000	--
	copper (Cu)	1,300 (AL)	1,000	--	200	500	--
	cyanide[3] (CN^-)	200	--	--	--	--	--
	iron (Fe)	--	300	--	5,000	--	--
	lead (Pb)	15 (AL)	--	--	5,000	100	--
	lithium (Li)	--	--	--	2,500	--	--
	manganese (Mn)	--	50	--	200	--	--
	mercury (Hg)	2	--	--	--	0.05	--
	molybdenum (Mo)	--	--	40	--	--	--
	nickel (Ni)	--	--	100	200	--	--
	selenium (Se)	50	--	--	20	50	--
	silver (Ag)	--	100	--	--	--	--
	thallium (Tl)	2	--	--	--	--	--
	vanadium (V)	--	--	--	100	100	--
	zinc (Zn)	--	5,000	2,000	2,000	25,000	--
Nutrients (mg/L)	nitrate (NO_3^-), as N	10	--	--	--	--	--
	nitrite (NO_2^-), as N	1	--	--	--	10	--
	nitrate + nitrite, as N	10	--	--	--	100	--
	ammonium (NH_4^+), as N	--	--	30	--	--	--
Radiochemicals (pCi/L unless otherwise noted)	gross-alpha radioactivity[4]	15	--	--	15	15	--
	strontium-90 (strontium)	--	--	4,000 (µg/L)	8	8	--
	radium-226 plus radium-228	5	--	--	5	5	--
	radon-222 (radon)[5]	300/4,000 (proposed)[5]	--	--	--	--	--
	uranium (µg/L)	30	--	--	--	--	--

[1]Selected from U.S. Environmental Protection Agency 2012 edition of the Drinking Water Standards and Health Advisories (U.S. Environmental Protection Agency, 2012).

[2]Selected from Wyoming Department of Environmental Quality Water Quality Rules and Regulations, Chapter 8, Quality Standards for Wyoming Groundwaters (Wyoming Department of Environmental Quality, 1993 [revised 2005], table 1, p. 9).

[3]Trace ion, included with trace elements for convenience.

[4]Includes radium-226 but excludes radon-222 and uranium.

[5]The 300 picocuries per liter standard is a proposed Maximum Contaminant Level, whereas the 4,000 picocuries per liter standard is a proposed alternative Maximum Contaminant Level for communities with indoor air multimedia mitigation programs (U.S. Environmental Protection Agency, 1999).

High chloride concentrations can adversely affect the taste of drinking water, increase the corrosiveness of water, and damage salt-sensitive crops (U.S. Environmental Protection Agency, 2012; Bohn and others, 1985, and references therein). The EPA SMCL for chloride is 250 mg/L, the WDEQ Class II groundwater (agricultural) standard is 100 mg/L, and the WDEQ Class III groundwater (livestock) standard is 2,000 mg/L. Low concentrations of fluoride in the diet have been shown to promote dental health, but higher doses can cause health problems such as dental fluorosis—a discoloring and pitting of the teeth—and bone disease (U.S. Environmental Protection Agency, 2012). The USEPA SMCL for fluoride is 2.0 mg/L, and the MCL is 4.0 mg/L.

Both iron and manganese may adversely affect the taste and odor of drinking water and cause staining (U.S. Environmental Protection Agency, 2012). The USEPA has established SMCLs of 300 micrograms per liter (µg/L) for iron and 50 µg/L for manganese. High concentrations of iron and manganese in irrigation water may have a detrimental effect on crop production (Bohn and others, 1985, and references therein).

5.5.1.5 Statistical analysis

In relation to groundwater quality, analysis has two meanings in this report, *chemical analysis* and *statistical analysis*. Chemical analysis of a water sample is the determination (or the description) of the concentration of chemical species dissolved in the water; for example, *the concentration of calcium in the sample is 6 mg/L* (6 milligrams of calcium per liter of water). The chemical analysis may include physical measurements of chemical properties such as pH (a measure of hydrogen ion activity). The statistical analysis of a *set* of chemical analyses is the mathematical treatment of the dataset to describe and summarize those data in order to convey certain useful descriptive characteristics; for example, *the calcium concentration in groundwater samples from this hydrogeologic unit ranges from 5.0 to 20 mg/L per liter, with a median concentration of 17 mg/L per liter*.

This section describes the approaches used to assemble, analyze, and present water-quality data for samples of groundwater from the Snake/Salt River Basin. From these data, *summary statistics* were derived for physical properties and major-ion chemistry of groundwater in hydrogeologic units in the Snake/Salt River Basin, as tabulated in **appendices E-1** to **E-6** for environmental water samples. *Environmental water* is natural groundwater as produced from wellheads and springs; it is not associated with hydrocarbons. *Produced water* is water co-produced (extracted from the ground) with oil and gas or water samples collected during exploration for oil and gas. The water-quality data for the hydrogeologic units in the Snake/Salt River Basin also are compared to USEPA and WDEQ standards for various water uses, as the *groundwater-quality standard exceedance frequencies* presented in this report.

Standard summary statistics (Helsel and Hirsch, 1992) for uncensored data were used for physical characteristics and major-ion chemistry of environmental water samples (**appendices E-1** through **E-6)**. Censored data are data reported as above or below some threshold, such as “below detection limit” or “less than (<) 1 mg/L.” For very few major-ion samples, censored values (“less-than”) were reported for a major-ion constituent. These censored values were treated as uncensored values at the laboratory reporting level, for statistical analysis. For uncensored datasets with a sample size of 1, only a minimum value is reported in **appendices E-1** through **E-6**; for a sample size of 2, minimum and maximum values are reported; for a sample size of 3, minimum, median (50th percentile), and maximum values are reported; for sample sizes of 4 or more, minimum, 25th percentile, median (50th percentile), 75th percentile, and maximum values are reported. Concentrations of nutrient, trace element, and radiochemical constituents were reported as uncensored values in environmental water datasets for some hydrogeologic units. For nutrient, trace element, and radiochemical datasets without censored values, the convention used for uncensored data was used to report summary statistics. Environmental water datasets for other hydrogeologic units contained censored values, including censored values that had multiple detection limits. Rather than assign the laboratory reporting level or another arbitrary value to the censored results, the Adjusted Maximum Likelihood Estimation (AMLE) technique was used for statistical analysis of nutrients, trace elements, and radiochemical constituents in this report. The AMLE technique is for left-censored data and computes summary statistics for results with multiple detection limits (Helsel and Cohn, 1988). The technique requires that at least three values are uncensored for a sample size of three or greater and that the proportion of censored values does not exceed 90 percent in order to compute percentiles. The AMLE technique computes statistics for the interquartile range and determines the maximum uncensored value for the dataset; therefore, the summary statistics presented in the report for nutrients, trace elements, and radiochemical constituents are the 25th percentile, median, 75th percentile, and maximum. In some cases, environmental water datasets for a constituent and hydrogeologic unit could not meet the minimum sample size or uncensored value requirements for the AMLE technique. In those cases, constituents within a hydrogeologic unit that had a sample size of 1, a minimum value (censored or uncensored) is reported, and for a sample size of 2 or greater, a minimum value (censored or uncensored) and maximum value are reported, or only a maximum censored value is reported. For a few constituents that did not have any censoring, standard summary statistics could be determined and are reported. In some cases, a dataset for a constituent and hydrogeologic unit was insufficient for determining complete summary statistics with the AMLE technique; however, individual samples could be used for groundwater-quality exceedance analysis.

Groundwater-quality standard exceedances frequencies are described for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards. Groundwater-quality standard exceedances were calculated and reported as the number of samples with exceedances out of the total number of quality samples analyzed for that property or constituent for a hydrogeologic unit. When only one sample was available and exceeded a standard, the text indicates one sample exceeded a standard, rather than indicating '100 percent.' Groundwater-quality standard exceedances frequencies were determined using the filtered analyses for a constituent because filtered analyses were more common (or frequently were the only analyses available). Only samples for a constituent that were analyzed at a laboratory reporting level that was equal to or less than the specific groundwater-quality standard for that constituent were included in the exceedance analysis. For example, if five samples were analyzed for manganese and the results were <10 µg/L, <20 µg/L, 53 µg/L, 67 µg/L, and <100 µg/L, only the four samples with results of <10 µg/L, <20 µg/L, 53 µg/L, and 67 µg/L could be compared to the SMCL of 50 µg/L for manganese. The sample with the value of <100 µg/L could not be used because it cannot be determined if its value was less than 50 µg/L or greater than 50 µg/L. For this example, the groundwater quality exceedance text would indicate that two of four samples exceeded the SMCL of 50 µg/L. Complete summary statistics for manganese would not be included in the appendix for the hydrogeologic unit in this example because too many of the available values were censored for the AMLE technique to calculate summary statistics. The AMLE technique criterion of having three uncensored values in the dataset was not met. For this example, only a maximum value of <100 µg/L would be reported in the appendix. Descriptions of the constituents that were included in the statistical summaries for environmental water samples are summarized in the next section.

5.5.1.5.1 Environmental water samples

Environmental water samples ("environmental waters") are from wells of all types except those used for resource extraction (primarily oil and gas production) or those used to monitor areas with known groundwater contamination. The environmental water samples used in this report were compiled from the USGS NWIS database, the WRDS database, and other sources such as consulting engineers' reports related to water supply exploration and development. The physical properties and constituents presented in this report are pH, specific conductance, major ions, nutrients, trace elements, and radiochemicals.

Physical properties of environmental waters, which generally are measured in the field on unfiltered waters, were pH (reported in standard units), specific conductance (reported in microsiemens per centimeter at 25 degrees Celsius), and dissolved oxygen (reported in mg/L). If field values were not available, laboratory values were used.

Major-ion chemistry of environmental waters, comprising major ions and associated properties or constituents, was reported as laboratory analyses of filtered waters (or constituents were calculated from laboratory analyses). Major-ion chemistry constituents and related properties were hardness (calculated and reported as calcium carbonate), dissolved calcium, dissolved magnesium, dissolved sodium, dissolved potassium, SAR (calculated), alkalinity (reported as calcium carbonate), dissolved chloride, dissolved fluoride, dissolved silica, dissolved sulfate, and TDS.

For this report, a measured laboratory value of TDS (residue on evaporation at 180 degrees Celsius) commonly was available and included in the dataset. If a laboratory value was not available, a TDS value was calculated by summing concentrations of individual constituents (if complete analyses were available). For this report, a filtered laboratory value of alkalinity was included in the dataset if available. If that was not available, an unfiltered laboratory value of acid-neutralizing capacity (ANC) was used for alkalinity; if that constituent was not available, a filtered field alkalinity value was used; and if that was not available, an unfiltered field value of ANC was used to report alkalinity. Some alkalinity values were computed from the bicarbonate reporting form to the calcium carbonate reporting form. These constituents are reported in milligrams per liter (mg/L).

Because there were many different types of laboratory analyses, including different analytical methods and different reporting forms (for example, concentrations reported as nitrate or as nitrogen), only a subset of the nutrient constituents were selected from the final datasets and used for calculation of summary statistics. Nutrient constituents in environmental waters, analyzed in a laboratory using filtered water samples, that were included in the summary statistics are dissolved ammonia (reported as nitrogen), dissolved nitrate plus nitrite (reported as nitrogen), dissolved nitrate (reported as nitrogen), dissolved nitrite (reported as nitrogen), dissolved orthophosphate (reported as phosphorus), dissolved phosphorus (reported as phosphorus), and dissolved organic carbon. Total ammonia (reported as nitrogen), total ammonia plus organic nitrogen (reported as nitrogen), and total phosphorus (reported as phosphorus), analyzed in a laboratory using unfiltered water samples, were included in the summary statistics. In addition, total organic nitrogen and total nitrogen, computed using analyses of the individual constituents, were included in the summary statistics. Nutrient constituents are reported in milligrams per liter (mg/L).

Trace element constituents in environmental waters, analyzed in a laboratory using filtered water samples, that were included in the datasets for this report were dissolved aluminum, antimony, arsenic, barium, beryllium, boron, cadmium, chromium, cobalt, copper, iron, lead, lithium, manganese, mercury, molybdenum, nickel, selenium, strontium, vanadium, and zinc. In addition, total iron (unfiltered) and total manganese (unfiltered) were included in the datasets. These constituents are reported in micrograms per liter (µg/L). Radiochemical constituents in environmental waters, analyzed in a laboratory using filtered water samples, that were included in the datasets for this report were gross alpha radioactivity, gross beta radioactivity, dissolved radium-226, dissolved radium-228, dissolved uranium (natural), and radon-222 (unfiltered) (referred to herein as “radon”). All radiochemical constituents are reported in picocuries per liter (pCi/L) except uranium, which is reported in micrograms per liter (µg/L).

5.5.1.5.2 Produced-water samples

Produced-water samples are from wells related to natural resource extraction (primarily oil and gas production). Chemical analyses for produced-water samples were compiled from the USGS PWD. Only two produced water samples from the USGS

PWD were located and are included in this report. The physical properties and constituents presented in this report for produced-water samples are pH, TDS, and major ions.

The physical properties and major ion chemistry for the two produced water samples included in this report generally were the same as for environmental waters, with some exceptions. In the produced-waters dataset, the water phase (filtered or unfiltered) was not reported with the data so the analyses may include a mix of dissolved and total concentrations. The physical properties and major-ion chemistry characteristics presented herein are pH (in standard units), calcium, magnesium, potassium, sodium, bicarbonate (reported as bicarbonate), carbonate (reported as carbonate), chloride, fluoride, silica, sulfate, and total dissolved solids (TDS). The method for determining TDS concentrations was not reported with the data. The reporting unit for major-ion chemistry was milligrams per liter (mg/L).

5.5.1.6 Trilinear diagrams

The relative ionic composition of groundwater samples from springs and wells in the Snake/Salt River Basin study area are plotted on trilinear diagrams for those hydrogeologic units with samples from at least three springs or three wells (**appendices F-1** through **F-6**). A trilinear diagram, also frequently referred to as a Piper diagram (Piper, 1944), provides a convenient method to classify and compare water types based on the ionic composition of different groundwater samples (Hem, 1985). Cation and anion concentrations for each groundwater sample are converted to total milliequivalents per liter (a milliequivalent is a measurement of the molar concentration of the ion, normalized by the ionic charge of the ion) and plotted as percentages of the respective totals into triangles (**appendices F-1** through **F-6**). The cation and anion relative percentages in each triangle are then projected into a quadrilateral polygon that describes a water type or hydrochemical facies (see Back, 1966).

5.6 Aquifer sensitivity and potential groundwater contaminant sources

This report provides an evaluation of the types of contamination that potentially threaten groundwater resources in the Snake/Salt River Basin. It is axiomatic that protecting groundwater from contamination is much more attainable than remediation should the resource be impacted by unsound practices.

In 1992, the Wyoming Department of Environmental Quality/Water Quality Division (DEQ/WQD), in cooperation with the University of Wyoming, the Wyoming Water Resources Center (WWRC), the Wyoming State Geological Survey (WSGS), the Wyoming Department of Agriculture (WDA), and the U.S. Environmental Protection Agency (EPA), Region 8, initiated the Wyoming Ground Water Vulnerability Mapping Project to evaluate the vulnerability of the state's groundwater resources to contamination. This effort resulted in the publication of the *Wyoming Groundwater Vulnerability Assessment Handbook* (the *Handbook)* by the Spatial Data and Visualization Center (SDVC; Hamerlinck and Arneson, 1998). While the fundamental goal of the SDVC study was to develop a GIS-based tool to aid in planning, decision-making, and public education, the GIS maps and associated digital databases developed by the project have been used for numerous subsequent, related studies such as updates to the State Water Plan. The SDVC aquifer sensitivity map and the associated GIS precipitation and recharge data are used in this study to evaluate aquifer-specific recharge (**chapter 6**). The methodology and purpose of the 1998 SDVC report are discussed in this section.

Two maps from the 1992 SDVC study are used to evaluate the potential for groundwater contamination in the Snake/Salt River Basin: 1) a map of average annual recharge (**fig. 5-2**), and 2) a map of aquifer sensitivity (**fig. 5-3**). **Figures 5-4** through **5-10** map potential groundwater contaminant sources in the Snake/Salt River Basin. Additional discussion on the rationale for and methodology used in developing **figures 5-1** through **5-10** is provided in **appendix C**.

5.6.1 The Wyoming Groundwater Vulnerability Assessment Handbook and aquifer sensitivity

The Wyoming Ground Water Vulnerability Mapping Project was initiated to develop GIS-based mapping approaches to: 1) assess the relative sensitivity and vulnerability of the state's groundwater resources to potential sources of contamination, primarily pesticides; 2) assist state and local agencies in identifying and prioritizing areas for groundwater monitoring; and 3) help identify appropriate groundwater protection measures. The *Handbook* distinguishes "groundwater vulnerability" and "aquifer sensitivity" as follows:

- *Aquifer sensitivity* refers to the relative potential for a contaminant to migrate to the shallowest groundwater, based solely on hydrogeologic characteristics. According to the SDVC, "Aquifer sensitivity is a function of the intrinsic characteristics of the geologic material between ground surface and the saturated zone of an aquifer and the aquifer matrix. Aquifer sensitivity is not dependent on land use and contaminant characteristics."

- *Groundwater vulnerability* considers aquifer sensitivity, land use, and contaminant characteristics to determine the vulnerability of groundwater to a specific contaminant. Because pollutant characteristics vary widely, the SDVC vulnerability assessments assumed a generic pollutant with the same mobility as water.

Aquifer sensitivity and groundwater vulnerability are characteristics that cannot be directly measured but must be estimated from measurable hydrogeologic and contaminant properties and land-use conditions. Because of the uncertainty inherent in the assessment of sensitivity and vulnerability, these parameters are not expressed quantitatively; but rather, in terms of relative potential for groundwater contamination. Because the SDVC vulnerability mapping assumed a single, generic pollutant, only the map of relative aquifer sensitivity is presented in this study. The aquifer sensitivity map **(fig. 5-3)** may be compared with **figures 5-4** through **5-10** to identify areas of elevated risk of contamination from specific potential groundwater contaminant sources.

The SDVC study assessed aquifer sensitivity using modified DRASTIC model methodology (Aller and others, 1985) based on six independent parameters:

- Depth to initial groundwater,
- Geohydrologic setting,
- Soil media,
- Aquifer recharge (average annual),
- Topography (slope), and
- Impact of the vadose zone.

The SDVC rates each parameter on a scale from 1 to 10 based on how strongly it affects aquifer sensitivity; a higher value indicates a greater effect. Parameter ratings are then summed to obtain an index of sensitivity that ranges from 6 (lowest risk) to 60 (highest hazard).

There are substantial limitations associated with the SDVC sensitivity analysis and maps. The sensitivity map portrays only a relative assessment of susceptibility to groundwater contamination. The Wyoming sensitivity assessments cannot be compared to similar studies in adjacent states or other areas. The sensitivity assessments are not appropriate for stand-alone, site-specific application, and should be supplemented with additional investigations.

Figure 5-3 delineates five sensitivity categories for the Snake/Salt River Basin that reflect the relative potential for contaminants to migrate from the ground surface to the uppermost groundwater (water table).

- The highest risk areas (43-56) are located primarily over alluvial deposits; adjacent to rivers, streams, and lakes; and in the highly fractured mountain belts that surround the basins. The shallow depths to groundwater, high porosities of unconsolidated soils and weathered bedrock, and relatively flat topography place alluvial aquifers at higher risk of contamination. Similarly, heavily fractured bedrock, shallow groundwater within thin soil zones, and high rates of recharge characteristic of mountainous aquifers make fractured mountain units highly vulnerable to contamination.

- Medium-high ranked areas (37-42) generally extend from the edges of the highest ranked areas, across adjacent alluvial or foothill zones. Groundwater in these areas generally occurs in deeper, thinner aquifers. The soils in these zones are more mature and have higher clay and loam contents. There is less fracturing in the bedrock exposed in the foothills than in more highly deformed, mountainous areas.

- Medium ranked areas (31-36) are prevalent in the remaining dry land agricultural and grazing areas of the Snake/Salt River Basin. These areas generally have relatively thicker, well-drained, mature soils; rolling topography with minor relief (lower slopes); and greater depths to the water table.

- Medium-low ranked areas (26-30) are generally characterized by low natural precipitation, low recharge, deep water tables, rolling topography, and unfractured bedrock.

- Low ranked areas (18-25) have the deepest water tables and lower hydraulic conductivity in the vadose zone. Soils in these areas are generally poor for agriculture due to high clay content, or due to very low average precipitation, or both.

5.6.2 Potential sources of groundwater contamination

Figures 5-4 through **5-10** illustrate potential groundwater contaminant sources in the Snake/Salt River Basin. These generally include industrial, retail, private, and public facilities that manufacture, process, use, store, sell, dispose, or otherwise handle substantial volumes of waste and other substances with physical and chemical characteristics that, released to the environment, could migrate to the water table. Releases from these facilities would pose a potential threat primarily to unconfined aquifers and the outcrop/recharge areas of confined aquifers. **Figure 5-3** shows areas where migration to the water table is most likely.

Many human activities have the potential to contaminate underlying groundwater resources. Possible sources of contamination include the following broad economic sectors: farming and ranching; resource development such as mineral extraction and logging; construction; transportation; residential, industrial and commercial development; and recreational activities. This section examines the potential for contamination from various point sources, that is, sources of pollution that can be traced to single definable places.

The identification and mapping of facilities as potential sources of groundwater contamination ***does not*** imply that they are impacting groundwater resources. Generally, these facilities are strictly regulated by one or more regulatory agency to prevent contaminant releases and to protect groundwater resources, human health, and the environment.

The following regulatory agencies, and the types of facilities that they regulate, provided the geospatial data used to generate **figures 5-4** through **5-10**:

WDEQ Water Quality Division:

- Known contaminated sites regulated under the Groundwater Pollution Control Program;
- Class I and V injection wells regulated under the Underground Injection Control (UIC) Program;
- Wyoming Pollutant Discharge Elimination System (WYPDES), formerly National Pollutant Discharge Elimination System

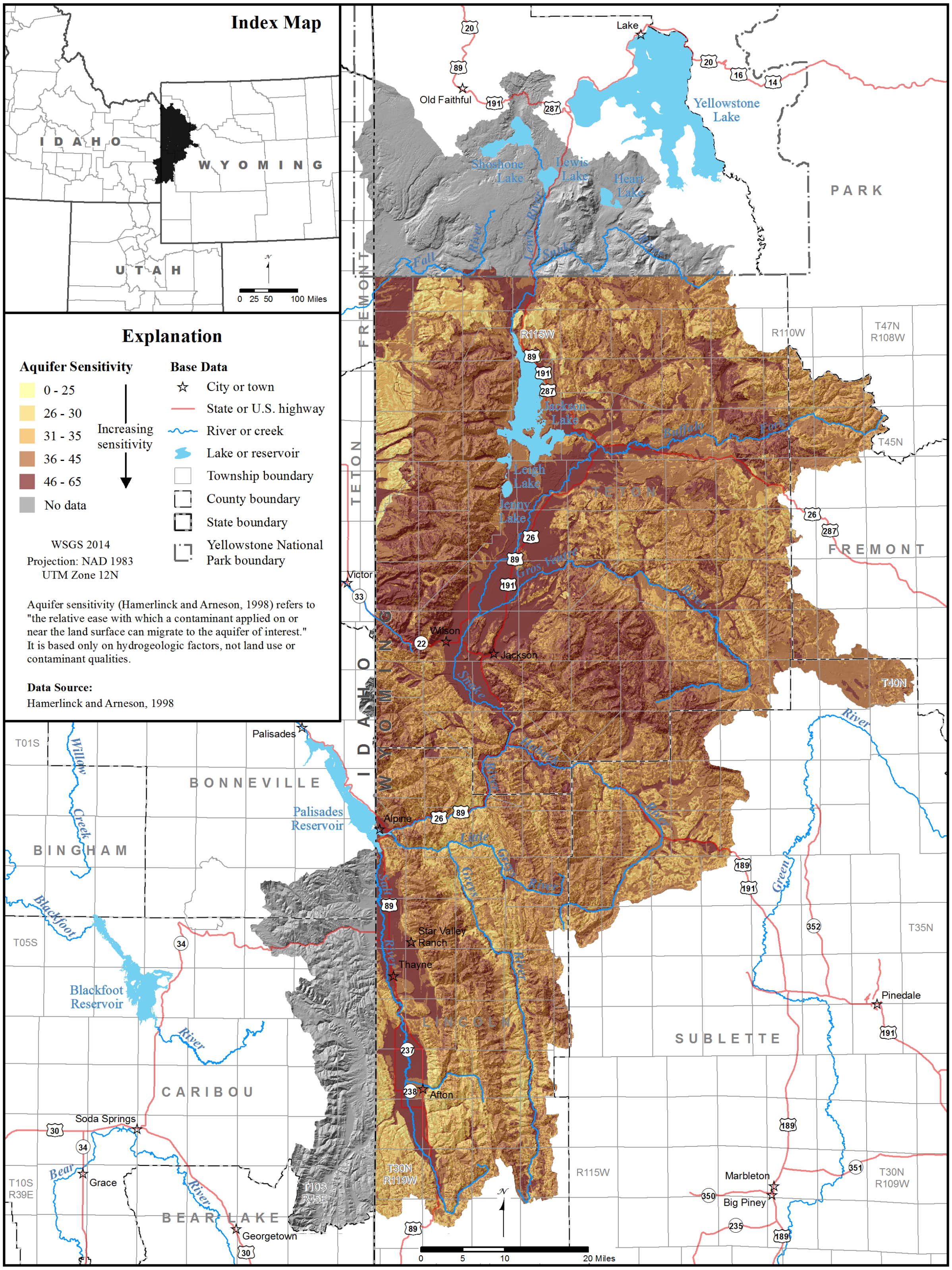

Figure 5-3. Aquifer sensitivity, Snake/Salt River Basin, Wyoming.

(NPDES), discharge points;
- Public owned treatment works (POTWs) and septic systems (Water and Wastewater Program);
- Confined animal feeding operations (CAFOs);
- Pesticides/herbicides (Nonpoint Source Program), and;
- Underground coal gasification sites.

WDEQ Solid and Hazardous Waste Division:
- Known contaminated sites regulated under the Voluntary Remediation Program (VRP), including orphan and brownfield assistance sites;
- Permitted disposal pits and other small treatment, storage, and disposal (TSD) facilities;
- Landfills, and;
- Above-ground and underground storage tanks.

WDEQ Land Quality and Abandoned Mine Land Divisions:
- Class III injection wells used for mineral extraction;
- Active, inactive, and abandoned mines, gravel pits, quarries, etc.

Wyoming Oil & Gas Conservation Commission:
- Active and abandoned Class II disposal and injector wells, and;
- Produced water pits.

Wyoming State Geological Survey:
- Oil and gas fields, plants, compressor stations;
- Pipelines;
- Mines (active and inactive), and;
- Gravel pits, quarries, etc.

These agencies were contacted to obtain available data suitable for mapping the various potential contaminant sources. Location data for similar potential contaminant sources were grouped for presentation on an abridged version of the surface hydrogeology map (**pl. 2**): the groupings in **figures 5-4** through **5-10** are generally not by agency, but rather by similarity of facilities and presentation considerations, primarily data point density. Some areas of high data density have been scaled up as inserts on the potential contaminant sources maps.

Figure 5-4 – Potential groundwater contaminant sources: Oil and gas fields, pipelines, refineries, and WOGCC Class II injection and disposal wells

The sole petroleum infrastructure shown in **figure 5-4** is the Hoback Canyon gas delivery pipeline. Additional information about petroleum infrastructure can be obtained online from: http://wogcc.state.wy.us/.

- **Oil and gas fields:** WOGCC records indicate that oil and gas wells in the Snake/Salt River Basin were exploratory wells only, and they have all been plugged and abandoned. The three gas fields shown in **figure 5-4** (Sohare, Cabin and Game Hill) contained only wells that never produced significant quantities of oil, natural gas or produced water.

- **Pipelines:** Inter- and intrastate pipelines transport a variety of liquids that if released by rupture, malfunction, operational problems, or leaks can migrate to groundwater. Small leaks from buried pipelines can go undetected for extended periods of time, releasing substantial volumes of contaminants. The sole petroleum infrastructure shown in **figure 5-4** is the Hoback Canyon gas delivery pipeline.

- **Active and permanently abandoned injector and disposal wells:** Wells for disposal or for maintaining reservoir pressure in enhanced oil recovery, among other purposes, are permitted by the WOGCC for injecting produced water into permeable zones that are deeper than and hydraulically isolated from useable groundwater resources. Class II wells, strictly regulated by the WOGCC and the BLM/EPA, generally pose minimal potential for impacting groundwater resources by excursions from the injection interval; however, releases during surface operations or through poorly cemented well casing, though rare, are potential avenues of contamination. Class II injection wells are located within oil and gas fields. There are no WOGCC injection or disposal wells in the Snake/Salt River Basin.

Figure 5-5 – Potential groundwater contaminant sources: Class I and V injection wells in the WDEQ UIC Program

- **Class I and V UIC injection wells:** Class I underground injection wells and Class V injection facilities are regulated through the WDEQ Underground Injection Control (UIC) Program. In Wyoming, Class I wells inject non-hazardous wastes (Resource Conservation and Recovery Act (RCRA) definition) into hydraulically isolated, permeable zones that are deeper than, and isolated from, useable groundwater resources. Produced water disposal contributes a large component of injected fluids. Class I wells generally have minimal potential for impacting groundwater resources. Class I wells are mapped because of the wider range of liquid wastes they accept for injection. In contrast, Class V facilities inject a wide range of non-hazardous fluids generally above or directly into shallow aquifers, and therefore have a substantial capacity for impacting groundwater resources. Many Class V wells in Wyoming are associated with groundwater contamination, and new injection of industrial wastes has been banned. Currently, only three Class V facilities permitted to inject industrial wastes are operational in the state of Wyoming and these must follow stringent annual monitoring requirements. Some notable examples of Class V facilities are agricultural or storm water drainage wells, large-capacity septic systems and various types of infiltration galleries. Class I and Class V injection facilities also generally include bulk storage tanks, pipelines, and other equipment that could release contaminants in recharge areas.

- **Class III injection wells:** Class III injection wells are permitted through the WDEQ Land Quality Division (LQD). Class III wells inject fluids for in situ solution mining of various minerals (e.g., uranium, sulfur, copper, trona, potash), for underground coal gasification, for the recovery of hydrocarbon gas and liquids from oil shale and tar sands, and for experimental/pilot scale technology.

Figure 5-6 – Potential groundwater contaminant sources: WQD groundwater pollution control facilities, commercial oil pits, and active and expired outfalls in the Wyoming Pollutant Discharge Elimination System (WYPDES) program

- **Known contaminated areas:** These sites are generally regulated by the WQD Groundwater Pollution Control Program. They include sites with confirmed soil and groundwater contamination that have not entered the VRP and are being addressed under orders from the WDEQ.

- **Commercial wastewater disposal pits:** Commercial wastewater disposal pits are regulated by the WDEQ Water Quality Division (WQD) Water and Wastewater Program. These facilities deal primarily with produced water from oil and gas operations but can receive other wastes with prior approval of the WDEQ. Produced water disposed at these facilities is commonly accompanied by liquid hydrocarbons, which are generally recovered and sold prior to wastewater injection. Releases can occur from operational malfunctions, leaking from surface pits, and leaks from pipes and storage tanks.

- **Active and expired WYPDES outfalls:** Discharge of any potential pollutant from a point source into surface waters of the state requires a Wyoming Pollutant Discharge Elimination System (WYPDES) permit. During flow to surface waters where contaminant concentrations may be diluted, discharged waters may infiltrate dry drainages and recharge shallow aquifers, potentially contaminating groundwater resources. Spreader dikes, on-channel reservoirs, ponds, pits, and other impoundments are commonly installed along WYPDES flow paths to store

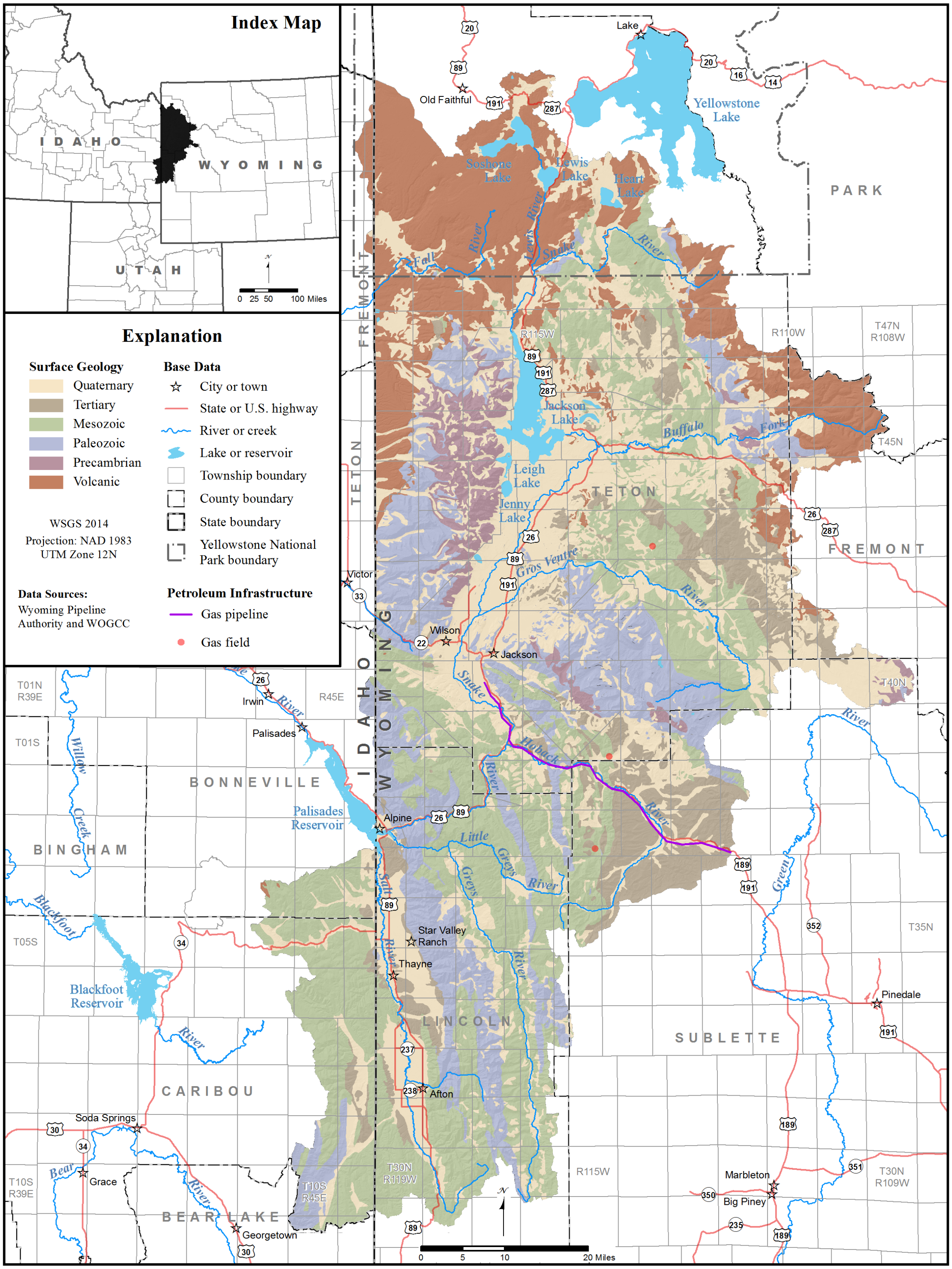

Figure 5-4. Potential groundwater contaminant sources: oil and gas fields, pipelines, gas processing plants, and Class II injection and disposal wells, Snake/Salt River Basin, Wyoming.

water for other uses, and to slow flow rates to minimize erosion and remove sediment. These installations all enhance the amount of surface flow that can infiltrate into the subsurface by increasing the time and area over which discharged water is in contact with the stream channel or storage basin. WYPDES outfalls are associated with a variety of facilities in the Snake/Salt River Basin.

Figures 5-7 through **5-9** show the locations of active and abandoned mines, quarries, pits, and similar operations. These facilities and sites can impact groundwater in several ways. Stripping topsoil from an area increases infiltration rates and removes the capacity for biodegradation and retardation of contaminants within the soil horizon. Excavations can impound large quantities of water and enhance recharge or can hydraulically connect contaminants to the water table. Atmospheric exposure of metal-rich minerals can oxidize and mobilize through dissolution. In addition, any release of bulk products (fuel, antifreeze, lubrication and hydraulic oils, etc.) more quickly infiltrates the subsurface within disturbed areas associated with the operations of these facilities.

Figure 5-7 – Potential groundwater contaminant sources: WDEQ/Abandoned Mine Land (AML) Program, abandoned mine sites - shows the location of abandoned mine sites inventoried and under the jurisdiction of the WDEQ AML Division. These include sites where reclamation may or may not have been completed.

Figure 5-8 – Potential groundwater contaminant sources: WDEQ Land Quality Division (LQD) permitted mines, quarries and pits

Three active mine types are regulated by the WDEQ Land Quality Division (LQD):

- **Active limited mining operations (LMO)** are exempt from the WDEQ's full permitting process. LMOs are restricted to a maximum of 10 acres for the life of the mine.
- **Active small mines** may disturb up to 10 acres per year but do not have a limit on the total area disturbed.
- **Active large mines** have no limit on total disturbance area or on how many acres may be disturbed per year.

Figure 5-9 – Potential groundwater contaminant sources: WSGS mapped mines, pits, mills, and plants - includes active, inactive, abandoned, and proposed facilities and sites, partially duplicating mine sites shown on **figures 5-8** and **5-9.** However, because the data for **figure 5-9** was compiled prior to and independently of the data compiled for **figures 5-7** and **5-8**, it might provide a more comprehensive picture of mining locations in the Snake/Salt River Basin.

Figure 5-10 - Volunteer Remediation Program (VRP) sites, storage tanks, solid and hazardous waste facilities - permitted by WDEQ Solid and Hazardous Waste Division (SHWD) including:

- o Municipal landfills and transfer, treatment, and storage facilities;
- o Industrial landfills, treatment, and storage facilities;
- o Solid waste treatment, storage, and disposal facilities;
- o Spill and hazardous waste corrective action sites, and;
- o Illegal dump sites and historic site cleanups.

- **VRP Sites:** These are sites where soil or groundwater contamination is remediated by agreement between the SHWD and the responsible party under the Voluntary Remediation Program (VRP).
- **Active storage tanks:** In use or temporarily out of use, above- and underground storage tanks are regulated by the WDEQ/SHWD Storage Tank Program. Because releases can go undetected for long periods of time, underground storage tanks (USTs) have long been recognized for their potential to contaminate groundwater. The Storage Tank Program was developed, in large part, in response to the high number of releases from USTs.

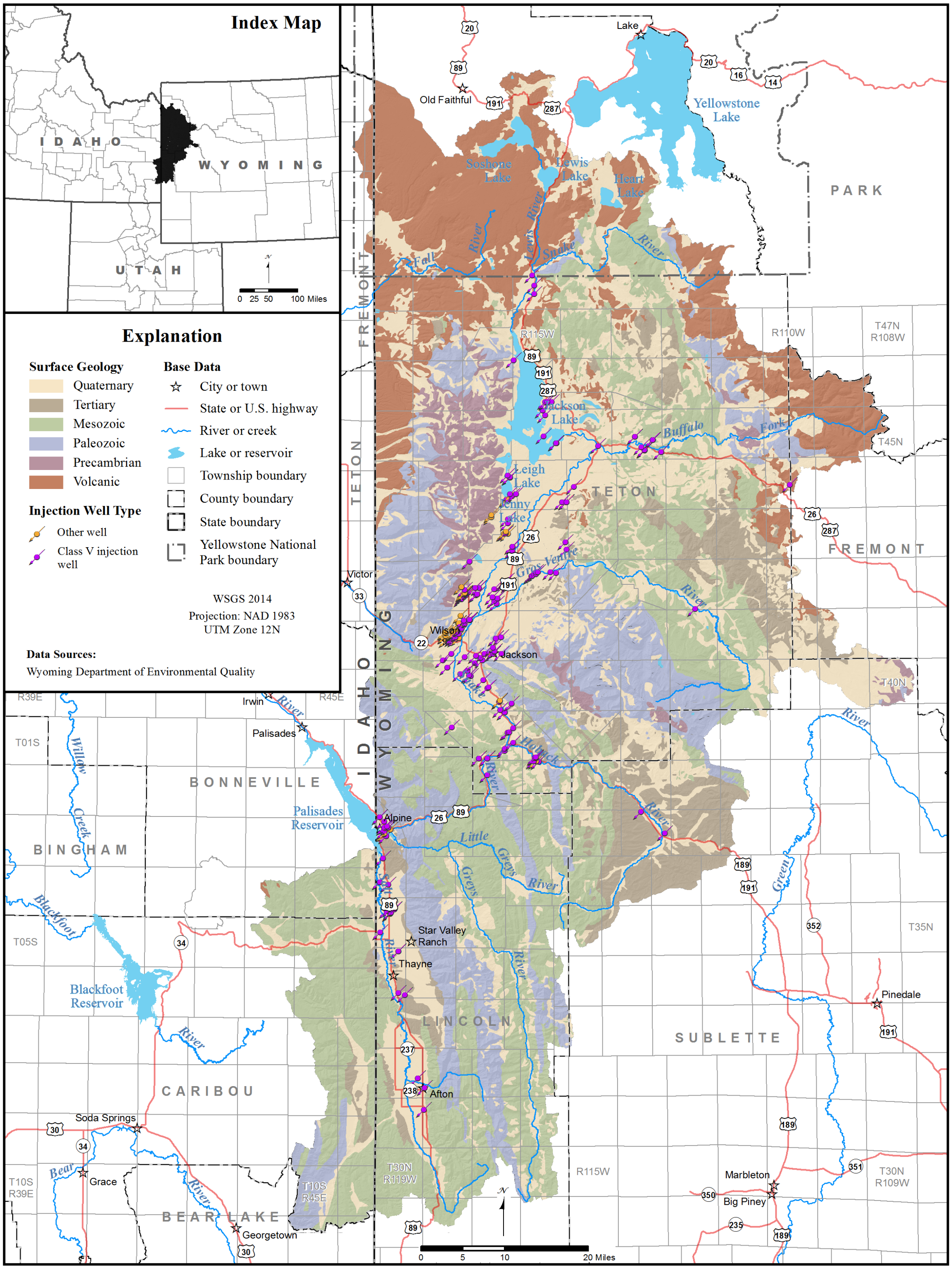

Figure 5-5. Potential groundwater contaminant sources: Class I and V injection wells permitted through the Wyoming Department of Environmental Quality Underground Injection Control (UIC) program, Snake/Salt River Basin, Wyoming.

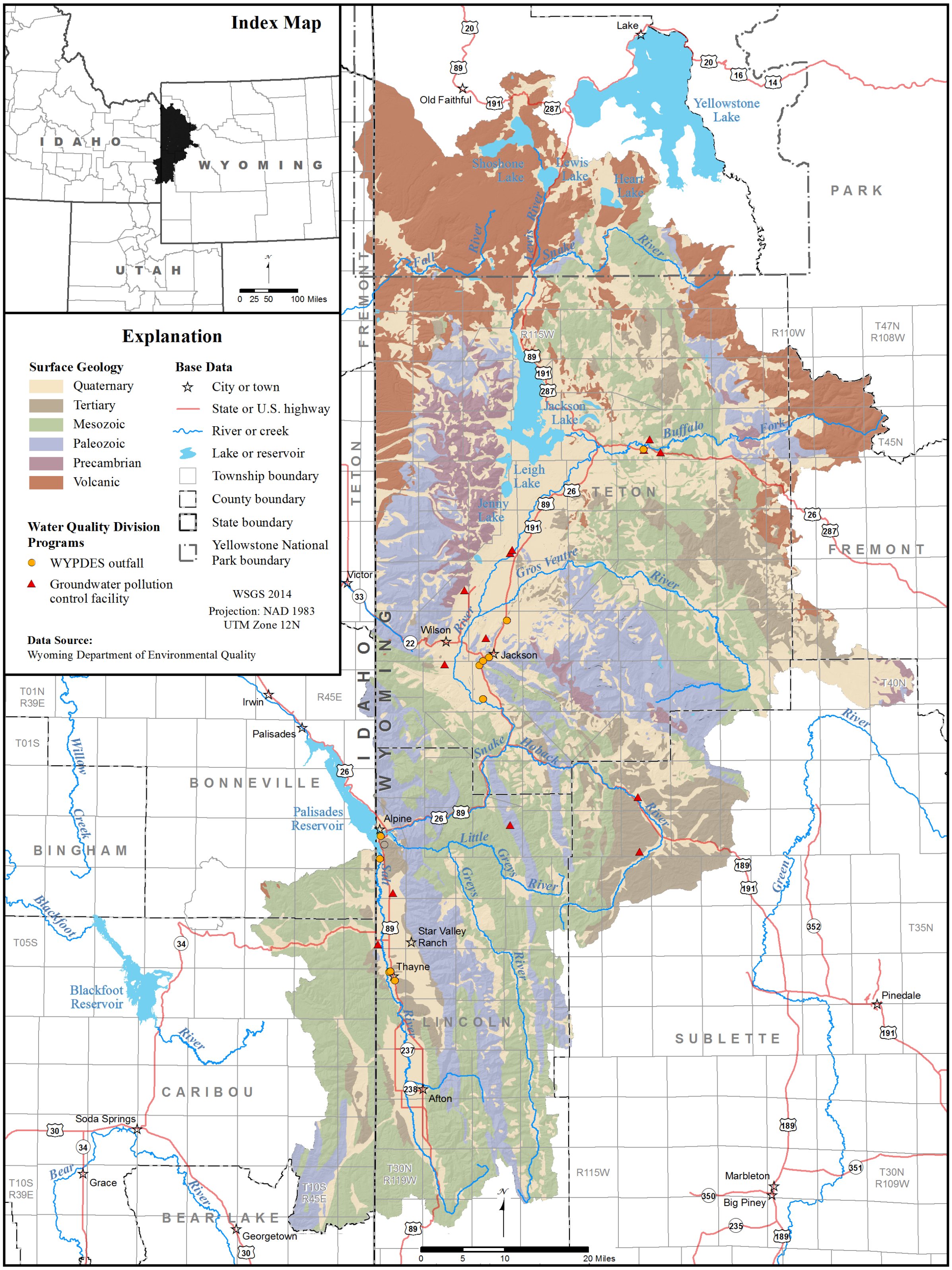

Figure 5-6. Potential groundwater contaminant sources: Active and expired outfalls in the Wyoming Pollutant Discharge Elimination System (WYPDES) program and WDEQ groundwater pollution control facilities, Snake/Salt River Basin, Wyoming.

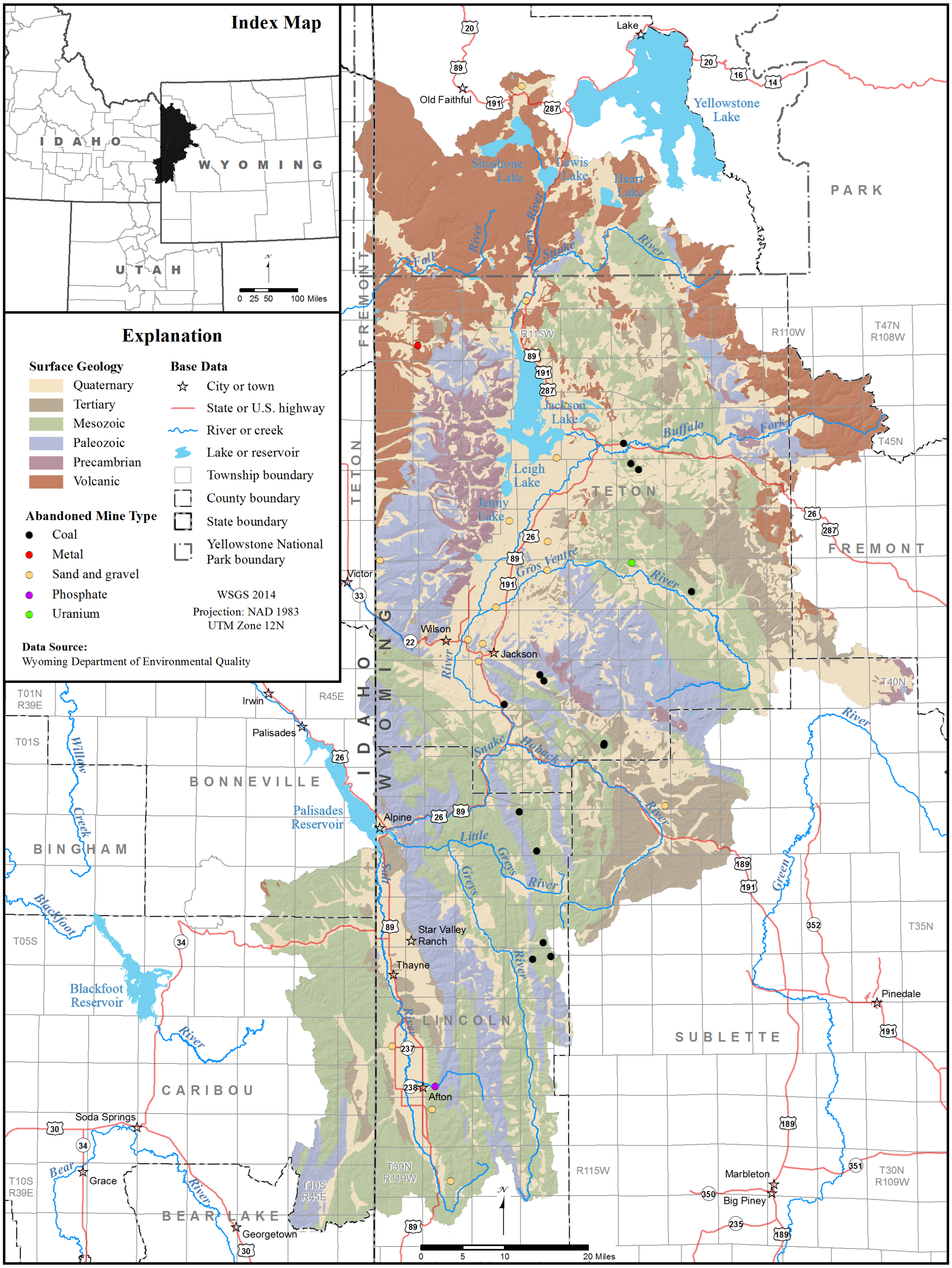

Figure 5-7. Potential groundwater contaminant sources: WDEQ Abandoned Mine Land Division abandoned mine sites, Snake/Salt River Basin, Wyoming.

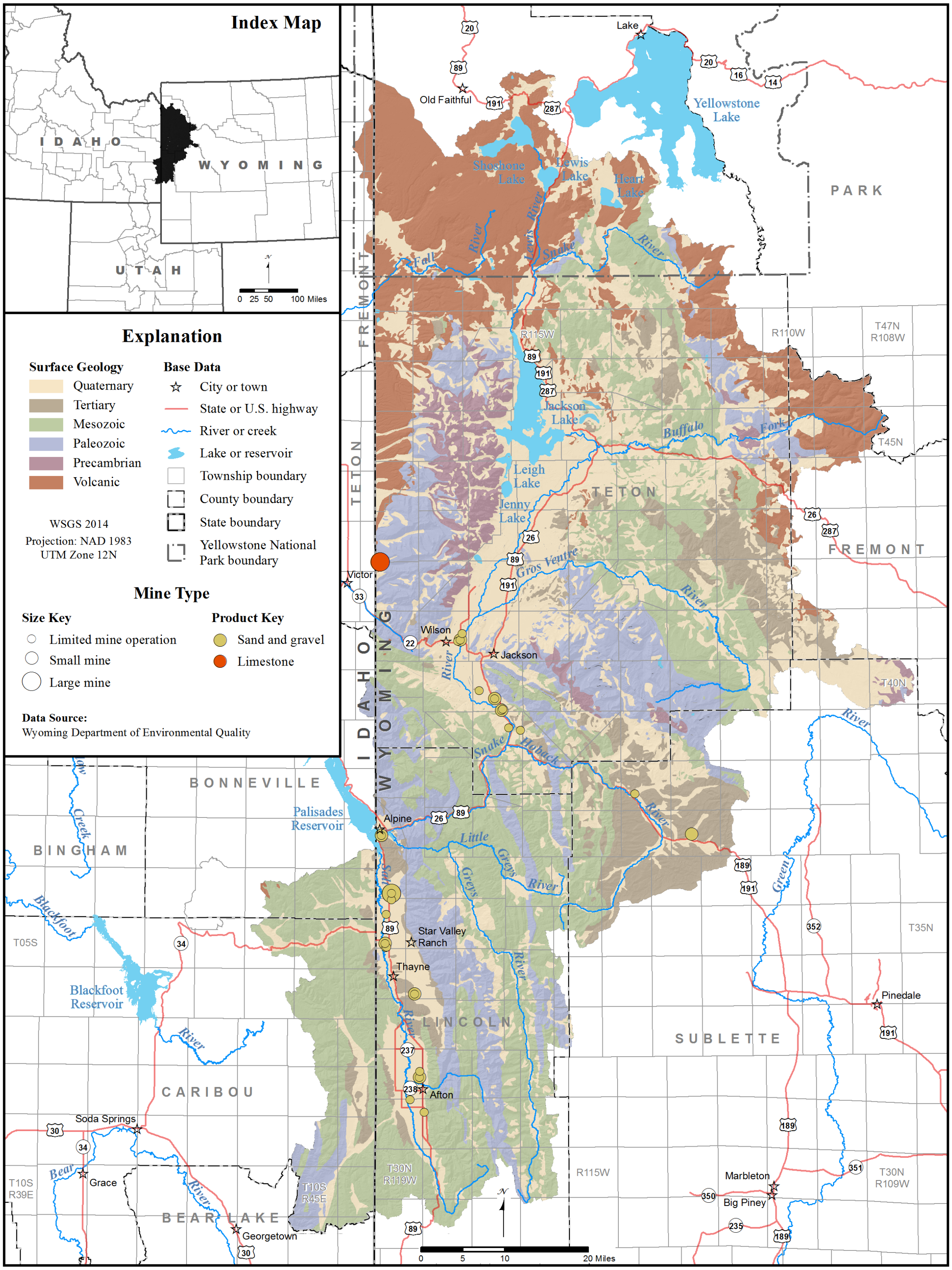

Figure 5-8. Potential groundwater contaminant sources: WDEQ Land Quality Division permitted mines, quarries and pits, Snake/Salt River Basin, Wyoming.

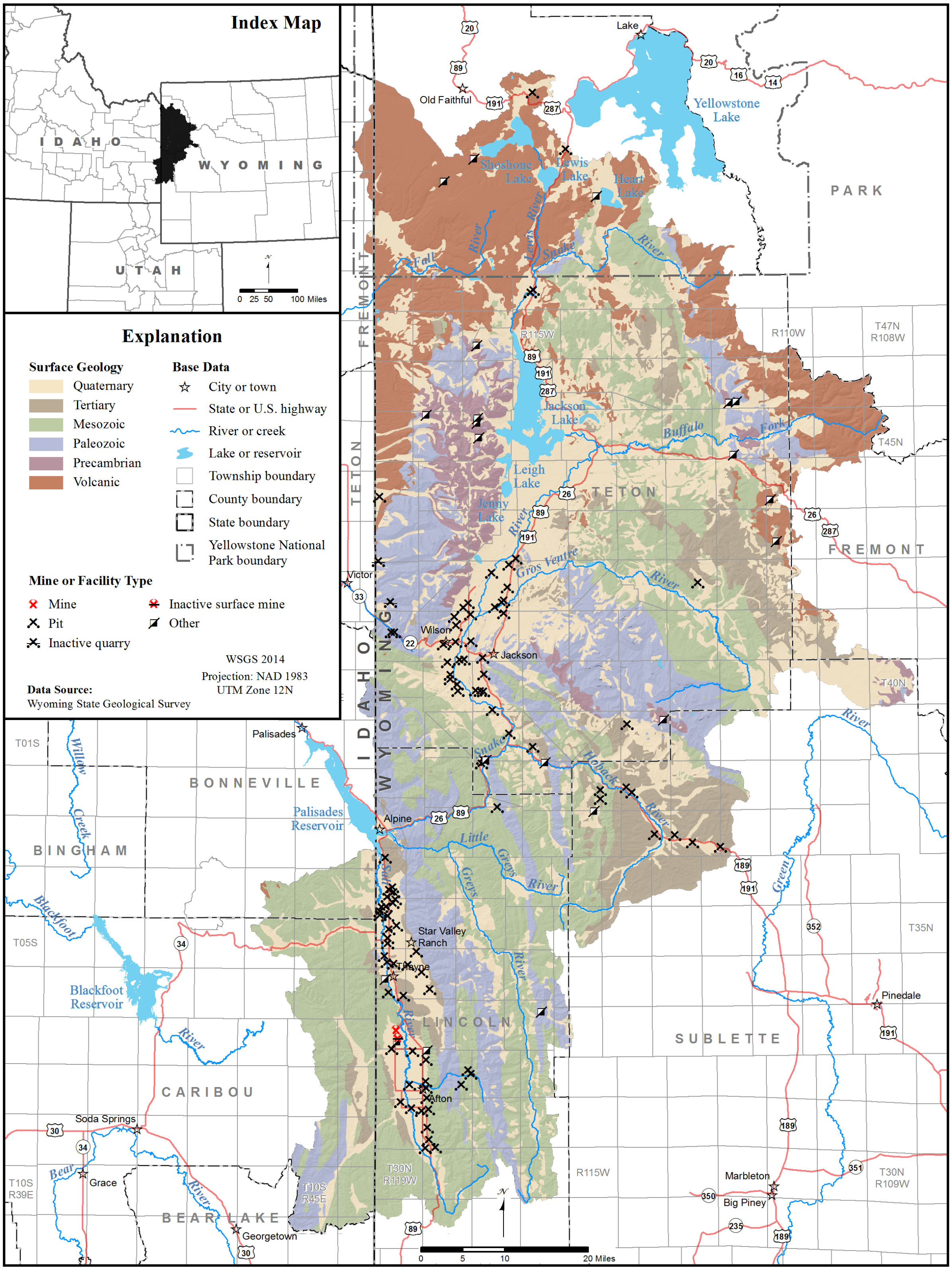

Figure 5-9. Potential groundwater contaminant sources: Wyoming State Geological Survey mapped mines, Snake/Salt River Basin, Wyoming, (locations from Harris, 2004).

- **Solid and hazardous waste facilities:** These contain a great number of potential contaminants in a variety of configurations. Wastes may be liquid, solid, or semisolid and stored either above or below ground in contained or uncontained repositories. Wastes are generally concentrated at these facilities, including concentrated liquid products that can leak from containers. Contaminants can migrate directly to shallow groundwater, or water from precipitation and other sources can infiltrate contaminant sources above the water table and form leachates composed of many contaminants. Active facilities usually store bulk contaminant products on-site (e.g., fuel, hazardous materials for recycling) that can also be sources of contamination if released.

5.6.3 Discussion

To be included in this study, location data for potential contaminant sources had to be in formats that could be imported into ArcGIS databases. Some contaminant source types do not currently have the location data in the ArcGIS format required for mapping, or the data exist but were unavailable. The following types of potential groundwater contaminant sources were not mapped in this study:

- Although a number of public owned treatment works (POTWs) and septic systems exist in the Snake/Salt River Basin, they were not mapped because adequate location data were not available. However, some large-capacity septic systems have been mapped as Class V injection facilities (**fig. 5-5**).

- Areas where pesticides and herbicides are applied were not mapped for this study. The distribution of irrigated lands presented in the 2003 Snake/Salt River Basin Final Report (Sunrise Engineering, 2003) shows the primary areas where agricultural chemicals would generally be applied in the Snake/Salt River Basin. In addition, recent USGS reports (Bartos and others, 2009; Eddy-Miller and Norris 2000; Eddy-Miller and Remley, 2004; Eddy-Miller and others, 2013) present the results of sampling to characterize pesticide occurrences in groundwater in areas determined by the earlier SDVC report (Hamerlinck and Arneson, 1998) to be most vulnerable to this type of contamination. The application of pesticides and herbicides is regulated by the WDEQ Nonpoint Source Program.

- There are currently no underground coal gasification (UCG) sites in the Snake/Salt River Basin.

- There are no WOGCC water pits, gas plants or compressor stations in the Snake/Salt River Basin.

- Construction/demolition landfills, hazardous waste and used oil generators, used oil transporter and storage facilities, one-time disposal authorizations, mobile treatment units, *de minimus* spills, and complaints were included in the data received from SHWD but are not shown on **fig. 5-10** due to variable location (mobile) or relatively low potential for contaminating groundwater.

The above list and description of potential groundwater contaminant sources may be incomplete. This study may have overlooked additional potential sources associated with sufficient volumes of contaminants of concern. Pending identification of additional potential sources and improvements in data (particularly location information) for the potential sources that were identified but not mapped for this study, it may be possible to include them in the next update to the Snake/Salt River Basin groundwater technical memorandum.

5.6.4 Source Water Assessment, Wyoming Water Quality Monitoring, and associated groundwater protection programs

The federal government, under the Clean Water Act, recognized that states have primary responsibility for implementing programs to

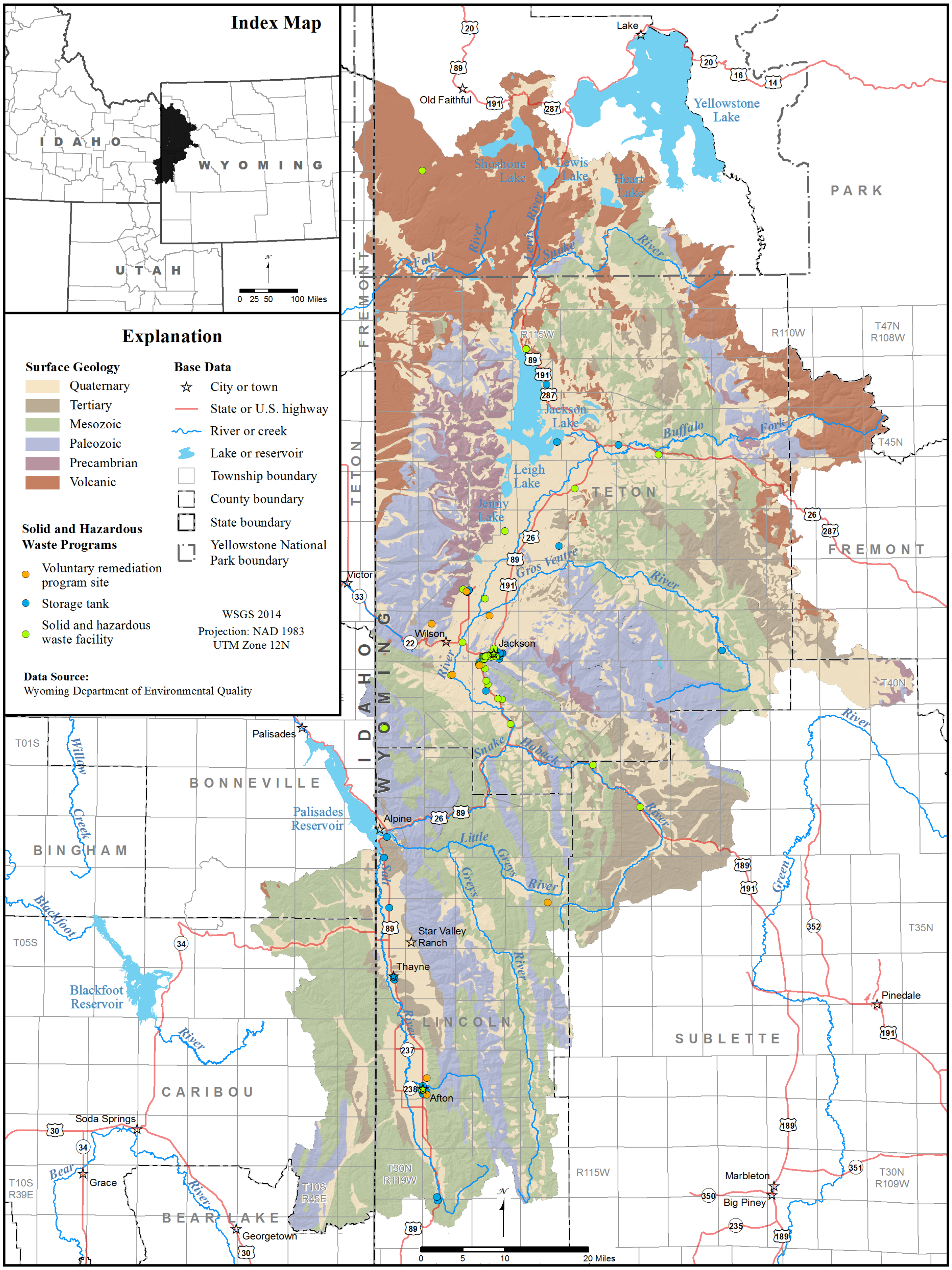

Figure 5-10. Potential groundwater contaminant sources: WDEQ permitted storage tanks, Voluntary Remediation Program (VRP), and permitted solid and hazardous waste facilities, Snake/Salt River Basin, Wyoming.

manage water quality. The primary objectives included under this broad responsibility are 1) establishing water quality standards, 2) monitoring and assessing the quality of their waters, and 3) developing and implementing cleanup plans for waters that do not meets standards. To meet the water quality monitoring objective, WDEQ, the USGS Wyoming Water Science Center, and other agencies have developed a suite of cooperative and complementary groundwater assessment and monitoring programs:

- Source Water Assessment Program (SWAP);
- WDEQ Water Quality Monitoring Strategy, led to the development of the Statewide Ambient Groundwater Monitoring Program also known as the Wyoming Groundwater-Quality Monitoring Network; and
- The USGS Pesticide Monitoring Program in Wyoming.

A general discussion of these programs follows. More information can be obtained from the WQD website at http://deq.state.wy.us/wqd/groundwater/index.asp under the Groundwater Assessment and Monitoring section.

The Source Water Assessment Program (SWAP)

The Source Water Assessment Program (SWAP), a component of the federal Safe Drinking Water Act enacted to help states protect both municipal and non-community public water systems (PWSs), provides additional information on potential local contaminant sources. The program, administered by the WDEQ Water Quality Division (WQD) and voluntary for the PWSs, includes the development of source-water assessments and protection plans, referred to as Wellhead Protection Plans (WHPs). The source-water assessment process includes: 1) determining the source-water contributing area, 2) generating an inventory of potential sources of contamination for each PWS, 3) determining the susceptibility of the PWS to identified potential contaminants, and 4) summarizing the information in a report. The development and implementation of SWAP/WHP assessments and plans is ongoing throughout Wyoming **(fig. 5-11)**.

Additional information on the SWAP in Wyoming can be accessed at: http://deq.state.wy.us/wqd/www/.

Water Quality Monitoring Strategy

Wyoming's strategy to develop an ambient groundwater quality database and a monitoring and assessment plan is designed to "determine the extent of groundwater contamination, update control strategies, and assess any needed changes in order to achieve groundwater protection goals" through a phased approach:

- Phase I – Aquifer prioritization (Bedessem and others, 2003; WyGISC, 2012)
- Phase II – Groundwater monitoring plan design (USGS, 2011)
- Phase III – Groundwater monitoring plan implementation and assessment
- Phase IV – Education and outreach for local groundwater protection efforts

Phases III and IV of the program are currently being conducted.

Phase I – Aquifer prioritization

The aquifer prioritization process was a cooperative effort between the University of Wyoming, WDEQ, USGS Wyoming Water Science Center, Wyoming Geographic Information Science Center (WyGISC), and Wyoming State Geological Survey (WSGS) designed to develop a GIS based approach to determine critical areas within high use aquifers using available aquifer sensitivity (Hamerlinck and Arneson, 1998) and water and land use data. The goals of this process were to identify and rank the areas and aquifers that should be included in the statewide ambient groundwater monitoring plan, presenting the results in a series of maps. To do this, the project team included the following layers in the GIS model:

- Aquifer sensitivity map of Hamerlinck and Arneson (1998)
- High-use aquifers less than 500 feet below ground surface
- High-use aquifer sensitivity
- Current water use (domestic and municipal)
- Land use:
    - Coal bed methane wells

- o Rural residential development
- o Oil and gas exploration, development, and pipelines
- o Known and potential contaminant sources
- o Croplands and urban areas
- o Mining
- o Composite land uses (up to six uses)

Based on these analyses, the Aquifer Prioritization Map distinguishes four relative priority categories within high-use aquifer areas (low, low-moderate, moderate-high, and high). Bedessem and others (2003) contains complete descriptions of the methods used and subsequent results; the article is available online at the DEQ website: http://deq.state.wy.us/wqd/groundwater/index.asp. The map can be accessed online: http://deq.state.wy.us/wqd/groundwater/downloads/map11.pdf.

Phases II and III – Groundwater monitoring plan design, implementation, and assessment

The groundwater monitoring plan was developed by the U.S. Geological Survey (USGS) and the Wyoming Department of Environmental Quality (DEQ) and instituted as the Wyoming Groundwater Quality Monitoring Network (WGQMN). The program is designed to monitor wells located in the priority areas and completed in the high use aquifers susceptible to contamination identified in Phase I.

Data collection and reporting by the USGS/WDEQ include the following:

- Water level measurement;
- Water sample collection and analysis for numerous natural and artificial constituents;
- Stable isotope analysis in selected samples to determine the nature and extent of aquifer recharge;
- Public access online reporting of water level and chemical analysis data at: http://water.usgs.gov/data/;
- Periodic publication of summary groundwater data in USGS Fact Sheets and Scientific Investigations Reports.

Program oversight is provided by a steering committee composed of representatives of the USGS, DEQ, EPA, WWDO, WSGS, and SEO. The steering committee meets periodically to evaluate program progress, and assess and modify program objectives.

Water quality analyses are conducted at the EPA Region 8 Laboratory in Denver, Colorado and other USGS laboratories. A complete description of the program and priority areas can be found online: http://pubs.usgs.gov/fs/2011/3041/.

Phase IV – Education and outreach for local groundwater protection efforts

The DEQ/WQD Groundwater Section provides extensive educational material and website links on its Web page: http://deq.state.wy.us/wqd/groundwater/index.asp.

Information on specific Wyoming aquifers can be found online at the Water Resources Data System Library: http://library.wrds.uwyo.edu/wwdcrept/wwdcrept.html, and in the USGS Publications website: http://pubs.er.usgs.gov/.

USGS Pesticide Monitoring Program in Wyoming

The USGS initiated a groundwater sampling program in 1995 to develop a baseline water quality dataset of pesticides in Wyoming aquifers. None of the 589 samples collected had pesticide levels exceeding the EPA Drinking Water Standards. The program is conducted in cooperation with DEQ and the Wyoming Department of Agriculture. Further program information and results are available online in USGS reports: http://pubs.er.usgs.gov/publication/fs03300, http://pubs.er.usgs.gov/publication/fs20043093,
http://pubs.usgs.gov/sir/2009/5024/,
http://pubs.usgs.gov/fs/2009/3006/,
http://pubs.er.usgs.gov/publication/fs20113011.

WDEQ Nonpoint Source Program

The goal of the Wyoming Nonpoint Source Program is to reduce the nonpoint source pollution to surface water and groundwater. The program directs efforts to reduce nonpoint source pollution, administers grants for pollution reduction

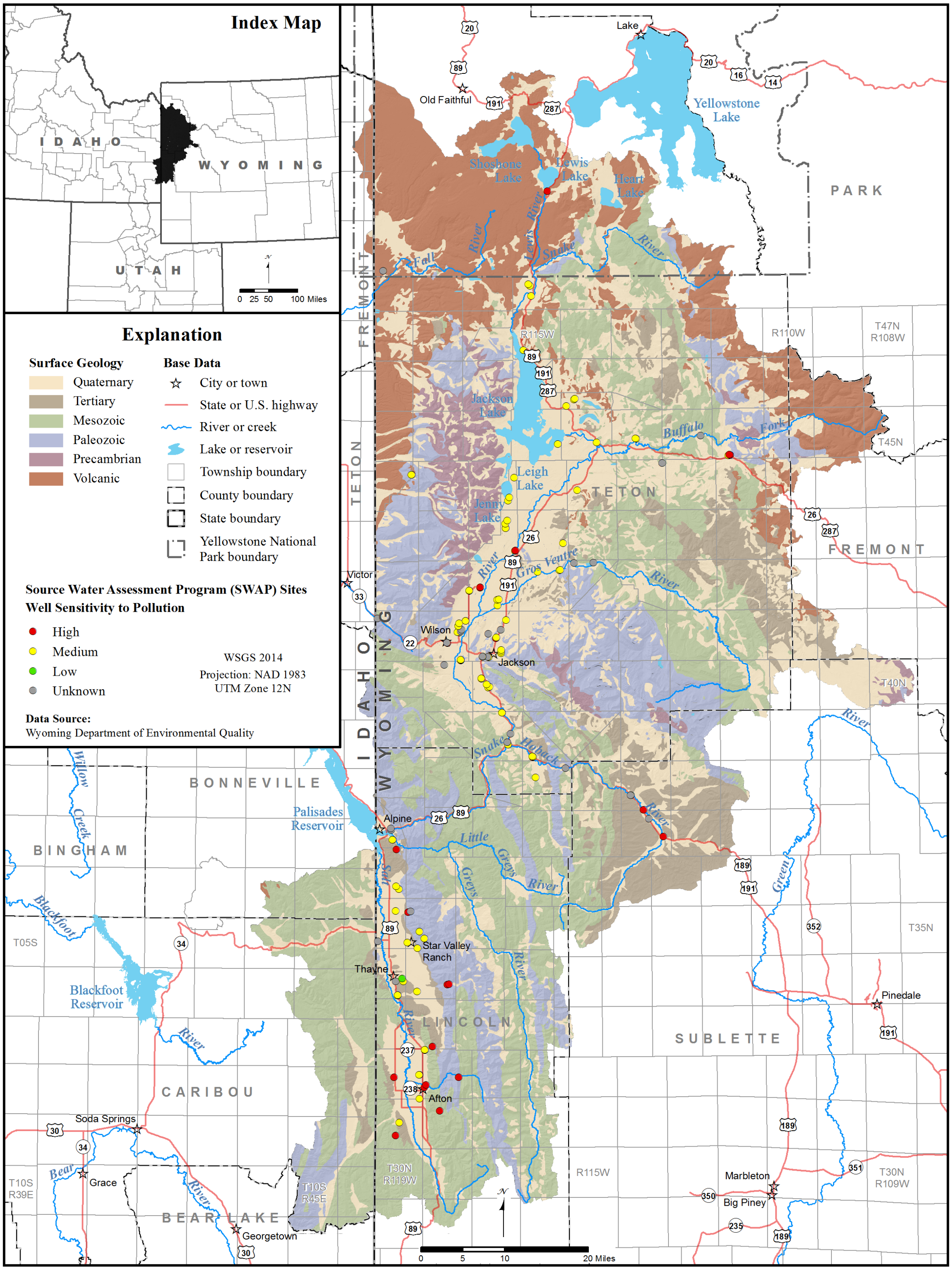

Figure 5-11. Surface Water Assessment and Protection, Snake/Salt River Basin, Wyoming.

efforts, and aids in watershed planning efforts. A 13 member steering committee, appointed by the Governor, provides program oversight and recommends water quality improvement projects for grant funding. More information about this program can be obtained online: http://deq.state.wy.us/wqd/watershed/nps/NPS.htm.

All three programs are intended to protect Wyoming's groundwater resources and inventory potential sources of contamination. The programs can be mutually beneficial by working together and including relevant information, either directly or by reference, to supplement their databases. Organizing as much groundwater quality and hydrogeologic information into an evolving master database would be useful in protecting and sustainably developing groundwater resources throughout Wyoming.