Chapter 5

Technical Concepts: Hydrogeology and Groundwater Quality

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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. Hydrogeologists 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. The shallowest 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 supplies. The hydrogeology of the deeper 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 (DEQ) class-of-use, water-quality standards **(Section 5.6.1; Chapter 7)**. Aquifer sensitivity, potential sources of groundwater contamination, 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 can be 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 (intergranular space), fractures of varying sizes, 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 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 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 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. It 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). Most *aquifer systems* also share the following characteristics:

- Regionally extensive.
- Common recharge and discharge areas and mechanisms.
- Similar hydraulic properties.
- Similar water-quality characteristics.
- 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 the movement of groundwater between the aquifers that it separates or between an aquifer and the ground surface. The hydraulic conductivity of a confining unit may range from essentially zero to a 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. Over large areas and extended periods of time, confining units can leak large 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 containing groundwater under atmospheric pressure that will rise and fall relatively quickly in response to recharge (e.g., precipitation, irrigation) 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 by and 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, or 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 deposits placed primarily by gravity at the foot of a hillslope.

Colluvium includes deposits such as 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 completed in that aquifer. Within an *unconfined aquifer* it is a physical surface. *Potentiometric surface* has generally replaced the older terms *piezometric surface* and *water table*. A synonym is *groundwater surface*. The *potentiometric surface* is generally mapped by equal-elevation contours in feet above mean sea level (ft-msl).

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; for while the *capillary fringe* above the *water table* is saturated, it is below atmospheric pressure. The term *water table* implies a flat, horizontal surface, but the actual surface is generally tilted or contoured like the land surface. In popular usage, the *water table* is the first occurrence of unconfined groundwater encountered below the ground surface 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 subject to an upward attraction.

Vadose zone – the depth interval between the ground surface and the water table that can include: 1) unsaturated soils, unsaturated bedrock, unconsolidated materials such as alluvium and 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 the well and surrounding wells are not being pumped and the *total head* in the aquifer is generally at equilibrium over a short time-frame. *Static head* or water level is commonly expressed in feet of elevation above mean sea level (ft-msl).

Drawdown – the lowering of the groundwater potentiometric surface (*head*) by discharge from an aquifer (pumping or natural discharge) 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 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, etc.) 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 changes in 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 (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. It can vary by direction; 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 x ft) or gallons per day, per foot (gpd/ft = gpd/ft^2 x ft). *Transmissivity* is equivalent to the hydraulic conductivity integrated over the thickness of an aquifer (x ft = 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 head. Like *specific yield*, *storage coefficient* is a dimensionless parameter because dimensions in 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, 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 conditions – occur 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 flow in the stream.

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).

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 a combination of these three basic types:

- *Porous flow* occurs through open, interconnected, intergranular spaces (pores) within a sedimentary geologic unit (generally conglomerate, sandstone, siltstone or unconsolidated deposit) 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 due to reduced friction with the relatively lower surface area within the larger 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,* that is, the porosity that results from deposition of the sediments and subsequent diagenetic processes such as compaction and cementation of the unfractured rock matrix.
- *Conduit flow* occurs through large, discrete open spaces (pipes, cavities, channels, caverns, other karstic zones), generally within relatively soluble sedimentary or evaporitic rocks such as limestone or dolomite, gypsum, anhydrite or salt. 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 developed during structural deformation (folding, faulting), joints in rocks developed during expansion (with uplift and erosion) or compaction, cleats (in coal), or fractures resulting from physiochemical alteration (shrinkage during desiccation, bedrock weathering, soil formation). 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 it 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

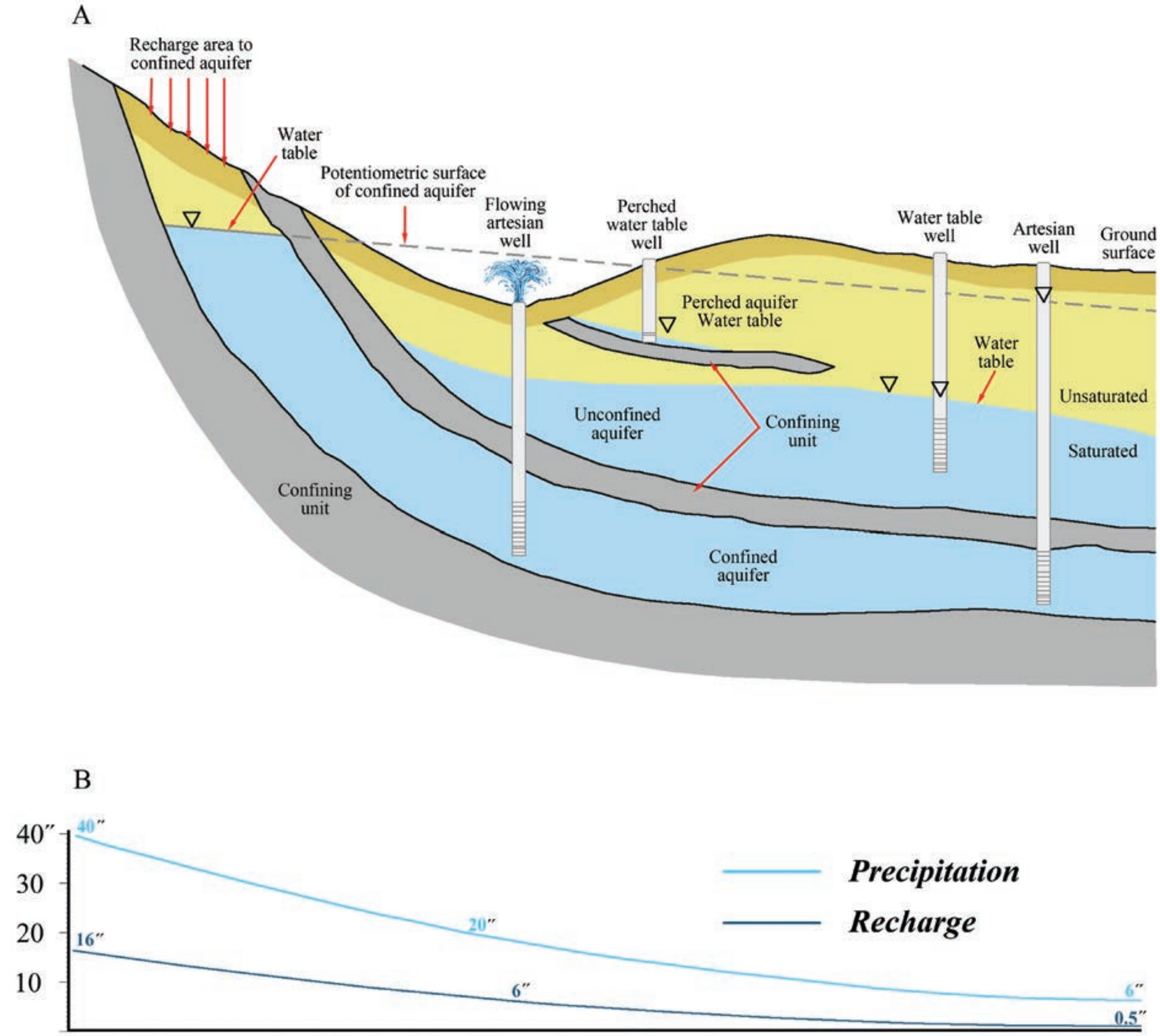

Figure 5-1. Conceptual cross-section of groundwater features that occur in a typical Rocky Mountain Laramide structural basin. Older hydrogeologic units outcrop and recharge at basin margins, dip steeply basinward, and become confined within short distances. Potentiometric surfaces for unconfined aquifers are marked with inverted triangles (water tables) and as a dashed line extending into the basin 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 Platte River Basin/recharge profile, in inches, basin margin to basin center. Adapted from WWC Engineering and others, 2007.

parameters to accurately quantify. Recharge cannot be measured directly, but must be estimated from other measurements and determinations.

In the relatively dry climate of Wyoming, the mountain ranges surrounding the basins receive high levels of precipitation (**Figure 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 when 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 basins 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, overland flow occurs and flows in nearby streams may be augmented. In that 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 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 conditions; 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 fractures in bedrock.
- Large natural (caves, animal burrows) and man-made (mines, pits) openings.
- Geospatial distribution, capacity and permeability of surface depressions.
- Opportunity for recharge from surface waters.
- Local land use (irrigation, soil stripping, paved areas).

Recharge can also occur by leakage from and through confining units into a receiving aquifer if permeability exists between the two units and the hydraulic gradient allows flow into the receiving aquifer. While the rate of leakage from confining units is by definition very slow, the volume of leakage may be quite substantial over time if the geospatial area of contact between the aquifer and confining unit 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 Platte River Basin. The extent of artificial recharge is difficult to evaluate on a regional basis, but might be determined for a local area.

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.

For this study, data from a statewide quantitative evaluation of recharge prepared by the Spatial Data and Visualization Center (SDVC) for the *Wyoming Ground Water Vulnerability Assessment Handbook* (Hamerlinck and Arneson, 1998) was modified to estimate recharge over the Platte River Basin **(Chapter 6)**. The original SDVC average annual recharge data is based on published percolation percentages for documented soil/vegetation combinations and average annual precipitation from 1961 through 1990 from the PRISM Climate Group. The SDVC calculated average annual recharge using the percentages; the SDVC general approach included:

- 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.
- 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) increases as the depth to the water table decreases.
- Recharge fraction increases as precipitation increases.
- Recharge fraction increases as the sand content of the soil increases.
- Recharge fraction 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.

Hamerlinck and Arneson also provide additional discussion on the methods they used to evaluate aquifer vulnerability and quantify recharge. A discussion of the various other methods for determining recharge rates is beyond the scope of this study.

In contrast to the 1961–1990 precipitation data used by Hamerlinck and Arneson (1998), this study uses updated precipitation data (PRISM Climate Group, 2012) for the 30 year period of record from 1981 through 2010. The average annual volumes of precipitation for the two periods of record are not significantly different. The PRISM data indicates that annual rainfall in the Platte River Basin averaged 19,935,860 acre-ft from 1961-1990 and 19,677,577 acre-ft from 1981-2010. It should be noted that the PRISM analyses that generated the two datasets used different cell sizes and the higher resolution (smaller cell size) of the 1981-2010 data more closely fits the boundary used for the Platte River Basin in this study. **Table 5-1** contains summary statistics for the two periods of record.

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 into streams (baseflow), wetlands, lakes, and other surface waters (especially within thick alluvial deposits, 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 natural discharge is difficult to determine, especially on a basin-wide basis. Some forms of discharge such as spring flows are readily measured. Others are difficult to quantify because they are concealed (leakage between geologic units or seepage into surface waters) or occur with wide variability over large areas (evapotranspiration). These discharges cannot be measured directly but must be estimated

Table 5-1 – Average annual precipitation statistics for the Platte River Basin for two 30 year periods of record, 1961–1990 and 198 – 2010 (PRISM Climate Group, 2012).

30 Year Period of Record	1961 - 1990	1981 - 2010
Average annual volume (acre-feet)	19,935,860	19,677,577
Calculated surface area (acres)	15,446,042	15,417,209
Weighted average annual precipitation (inches)	15.49	15.32

from other measurements and calculations; for example, using a mass balance (water balance) model if enough information on recharge and some discharges (e.g., surface water outflow, evapotranspiration) is available **(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. In some areas of the Platte River Basin, drainage tiles that discharge shallow groundwater directly to surface waters are installed in irrigated lands to lower the water table and prevent waterlogging and salt deposition. Groundwater withdrawals for beneficial use are estimated in the previous Water Plan (Trihydro Corporation and others, 2006a) and are discussed in **Chapter 8**.

Groundwater discharge, buffered by the storage function of an aquifer, is generally a more efficient process than recharge and occurs over smaller areas. 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 groundwater basin in question. Reasonable estimates of both recharge and discharge are necessary to evaluate safe/sustainable yield.

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 prevail 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 the deeper aquifers of a groundwater basin. The arrangement of aquifers and confining units that function as reservoirs and the plumbing system constitutes the framework of the groundwater flow system within a structural groundwater 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 and some springs that discharge groundwater from deep aquifers (**Figure 5-1**). 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 and low-angle to nearly horizontal within high-permeability units where friction is low. The slope of the potentiometric surface within a highly permeable aquifer is somewhat analogous to a standing body of water, such as a pond where there is no resistance to flow in any direction and the gradient due to gravity is 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 Platte 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 Platte River Basin occurs primarily in areas where they have been up-folded, eroded, and now crop out in the higher-elevation areas around the perimeters of the structural basins. These aquifers are unconfined at the outcrop areas, but as groundwater flows downdip from the recharge areas into the structural basins, 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 structural basins of the Platte River Basin is commonly controlled by structure and stratigraphy. Major aquifers and aquifer systems in the Platte 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 Platte River Basin is predominantly through permeable formations down-gradient (from higher to lower hydraulic pressure) and generally down-dip toward the axes of the structural basins. Where vertical permeable pathways exist, groundwater will follow them upward toward areas of lower hydraulic pressure.

5.1.4 Groundwater storage and safe / sustainable / optimal yield

In addition to functioning as the plumbing (conveyance) system for groundwater flow, the saturated geologic units that compose the framework of the Platte River Basin groundwater basins also function as reservoirs that store enormous volumes of groundwater. Understanding how groundwater is stored and how to utilize the resource without depleting it (safe/sustainable yield) is of concern in most development projects. An exception is coalbed natural gas (CBNG) development, where lowering hydraulic pressure in coalbed aquifers is the purpose of groundwater extraction.

An important aspect of groundwater resource assessments, on either a local or regional scale, is 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 put to beneficial use. Technical, financial, and cultural factors determine what fraction of the total volume of groundwater stored within a particular aquifer can be considered an available resource. That only part of the groundwater contained within an aquifer will be producible, and part will be retained within the aquifer fundamentally affects available volume. Development costs and water quality requirements are also primary factors that 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 5.6 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)**. Two of the most important hydraulic properties with respect to the sustainable development of groundwater resources are *specific yield* and *storage coefficient*.

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* 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). The sum of specific yield and specific retention equals *total porosity*. Because capillarity is higher in fine-grained materials (with 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. Highly productive unconfined aquifers are characterized by high specific yields.

The concept of *storage coefficient* can be applied to either an unconfined or a confined aquifer. 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 percentage or decimal fraction. 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, at which point the storage coefficient is essentially equal to the specific yield. Pumping an aquifer to the extent that recharge is inadequate to maintain confined conditions is referred to as "mining the aquifer."

The storage function of an aquifer operates as a buffer between recharge and discharge, 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, however, can induce recharge by 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 compression of the aquifer material.

The terms "safe yield" and "sustainable yield" have been used to describe the rate of groundwater production that can be sustained without causing an unacceptable level of depletion of storage volume or other negative effects, such as degradation of groundwater quality or depletion of surface water flows. A safe/sustainable yield estimate predicts the response of an aquifer to long-term withdrawals and recharge inflows. In reality, though, such projections are complicated by the fact that recharge is not delivered immediately. Aquifer response times can range from days to hundreds of years. For example, in the High Plains aquifer, Sophocleous (2005) estimated that an increase in soil moisture below the deep root level resulting from raised annual precipitation levels may not be delivered to the saturated zone as increased recharge for 144 years. Therefore, the changes in storage, currently observed, commonly reflect present day withdrawals and precipitation 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.

The concept of safe/sustainable yield has been applied over a wide range of scale, from individual wells to entire structural or drainage basins. Meinzer (1923, p. 55) defined the *safe yield* of an aquifer 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. Given these considerations, the definition given by Fetter (2001) is currently more applicable, *"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."* Because groundwater has value only to the extent that it can be put to a beneficial use, perhaps "optimal yield" in the context of a range of options from deliberately depleting (mining) an aquifer (e.g., for CBNG development) to total conservation (e.g., for wetlands maintenance) may be a more useful concept than safe/sustainable yield. In any case, end-users and resource managers must understand that any "yield" number will be dynamic and vary with time in response to changing cultural considerations, and environmental conditions such as extended drought.

Regional groundwater resources are generally evaluated within the conceptual model of a groundwater basin. Within this three-dimensional framework, the feasibility and sustainability of groundwater development can be analyzed by a conservation-of-mass approach variously referred to as a **water balance**, hydrologic budget, water budget, or hydrologic equation. 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)

Precipitation is the ultimate source of groundwater recharge, and both estimated precipitation and recharge have been mapped over the entire Platte River Basin (**Figures 3-3 and 5-2**). Discharge is more difficult to estimate. Considered on the scale of a groundwater basin, discharge is essentially composed of natural discharge to surface water that flows out of the basin, subsurface groundwater flows out of the basin in alluvial sediments underlying streams, evapotranspiration, and groundwater withdrawals that are not returned to the groundwater system. Long term changes in storage can be neutral (dynamic equilibrium), positive or negative. However, changes in aquifer storage must be evaluated for time periods that consider the response time of the target aquifer. This approach can be applied over a wide range of data density, with analyses often based on rough estimates of the variables in the water balance equation, especially for basin-wide studies. Accordingly, the results reflect the variability of the estimates.

In the best case for groundwater development within an aquifer with current withdrawals, groundwater in storage would be increasing, with long-term average recharge adequate to prevent depletion of storage. It is tempting and sometimes attempted, to estimate safe/sustainable yield as the amount of groundwater withdrawal that does not exceed average recharge. It is well known that this is not correct; however, the amount of water that can be withdrawn from a typical groundwater basin is fundamentally controlled by recharge, especially as withdrawal approaches or exceeds recharge. The water-balance equation shows that in addition to withdrawal, natural discharge also determines the amount of groundwater that is maintained in storage. The amount of water that can be

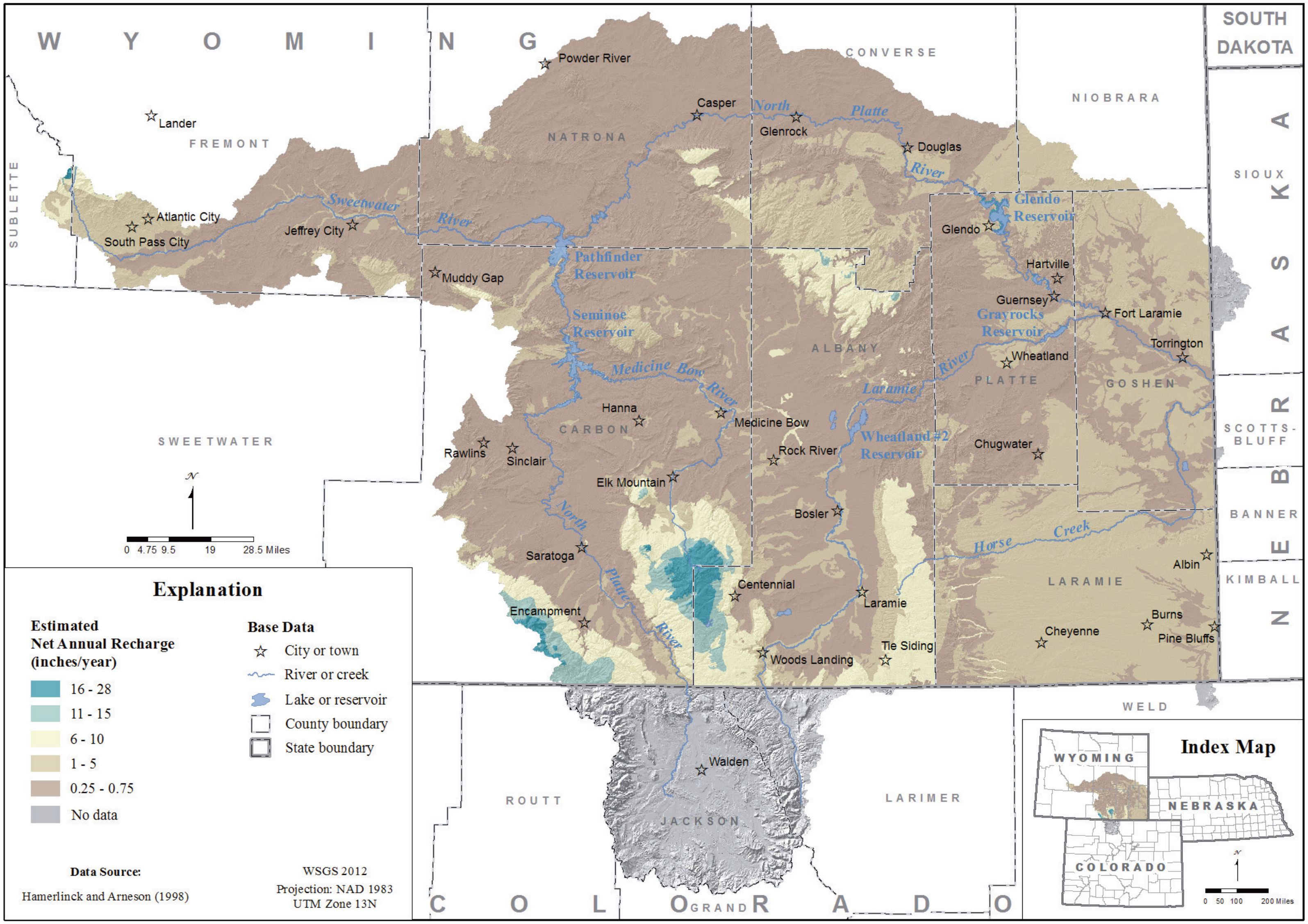

Figure 5-2. Estimated net annual aquifer recharge, Platte River Basin, Wyoming.

withdrawn from an aquifer or aquifer system that would not impact storage to an unacceptable degree might be defined as optimal yield – the portion of total discharge that is not already being utilized (existing withdrawals, baseflow to surface streams, etc.). Optimal development of all water resources within a basin would ultimately consider the conjunctive use of surface water and groundwater, especially where these resources are physically interconnected.

The unused or "available" part of <u>natural</u> discharge included in total discharge in the water balance equation is difficult to determine. Data for total discharge and its components, natural discharge and groundwater withdrawals, are generally not adequate to perform an evaluation using the water balance approach. The approach used in this study for evaluating groundwater resources **(Chapter 6)** is to consider average annual recharge over the areas of the aquifers exposed within Platte River Basin, restrained by a best estimate of total discharge. Average annual recharge rates for the Platte 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 Platte River Basin was prepared for this study **(Chapter 8)** using information provided in the previous Platte River Basin Water Plan (Trihydro Corporation and others, 2006a) 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 to estimate a range of "sustainable" groundwater resources in the Platte River Basin **(Section 8 and Chapter 9)**. Still, the estimates for natural and total discharge volumes are highly uncertain and may never be adequately resolved.

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

The geologic framework for the Available Groundwater Determination, Technical Memorandum for the Platte 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 affect recharge, storage, and groundwater flow. *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, and other *units* familiar to geologists.

The 2005 North American Stratigraphic Code 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 (Sheet II) of 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 charts contained in **Plates J, K, M, S, T, U** and **Figure 7.2**.

The Platte 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 Platte 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 charts are discussed in detail in **Chapter 7** regarding their component geologic or lithostratigraphic units.

Plates J, K, M, S, T, U and **Figure 7.2** also provide hydrostratigraphic information from previous studies so that informed readers can track the historical development of the basin's hydrostratigraphy. The hydrostratigraphic charts are 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 Platte 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 developed 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 has been made 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 present within this and other reports. Computerization greatly facilitated the process of organizing the GIS geologic units into hydrogeologic units and the development of the surface hydrogeology map and associated hydrostratigraphic chart provided as **Plate 2.** The **Plate 2** map of Platte River Basin surface hydrogeology is frequently referenced directly and is used throughout this study as a base for presenting the data compiled for water wells, springs, potential contaminant sources, and potential groundwater development areas. 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 Platte River Basin.

5.3 Wyoming statewide aquifer classification system

The 2007 Wyoming Statewide Framework Water Plan (WWC Engineering, Inc. 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 Platte River Basin. Under favorable conditions these aquifers can provide well yields of 500-1,000 gallons per minute (gpm). Yields are generally lower, however, in areas where the deposits are thin, contain abundant fine-grained material, are 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: These 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 lowland basin areas, the sandstone aquifers are mostly horizontal and some are widespread. Relatively thick Tertiary sandstone sequences that compose the High Plains aquifer system of southeast Wyoming are the most productive sandstone aquifers in the Platte River Basin. Older Mesozoic and Paleozoic sandstone aquifers exposed around the perimeters of the Platte River Basin structural basins commonly dip into the basins (**Plates 1** and **2**) and may contain accessible groundwater resources for several miles basinward of the outcrop areas. Groundwater quality tends to decrease with increasing depth into the basins. Some sandstone aquifers 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; however, coal beds and other strata can also yield substantial groundwater. 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. Limestone aquifers exhibit variable potential for development as wells can produce low yields up to very large quantities of good-quality water. 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. These aquifers are exposed primarily along the structural basin margins in the Platte River Basin (**Plate 2**), where deformation and potential for vigorous recharge and groundwater circulation are most prevalent. Examples include the Madison Limestone, the Casper Formation, and the Bighorn Dolomite. Depending on the degree of enhanced permeability, the major limestone aquifers can host accessible groundwater resources for several miles basinward 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 basinward.

Minor aquifer: These consolidated bedrock formations commonly provide groundwater for local use from relatively low-yielding wells (generally 50 gpm or less). Higher yields are available at some locations depending on local hydrogeologic and recharge conditions. 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 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 constitute the basal confining units below the sedimentary basins and represent 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, Inc. and others, 2007; Figure 4-9) classified the Platte River Basin geologic units as follows:

Major Aquifer - Alluvial

Quaternary alluvium

Major Aquifer - Sandstone

Wasatch and Wind River Formations
Fort Union Formation
Lance Formation
Fox Hills Formation
Cloverly/Dakota Formations

Major Aquifer - Limestone

Casper Formation, Tensleep Sandstone, Minnelusa Formation, and Hartville Formation
Madison Limestone and Bighorn Dolomite

Minor Aquifer

Quaternary non-alluvial deposits
Arikaree Formation
Mesaverde Formation or Group
Frontier Formation
Gallatin Formation, Gros Ventre Formation, and Flathead Sandstone

Marginal Aquifer

White River Formation
Sundance Formation

Major Aquitard (Confining Unit)

Meeteetse Formation and Lewis Shale Cody Shale, Pierre Shale, Steele Shale, Niobrara Formation, Baxter Shale, and Carlisle Shale
Thermopolis Shale, Mowry Shale, and Aspen Shale
Chugwater and Goose Egg FormationsPrecambrian 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 in this study for the Platte River Basin. Correlations between the 2007 Wyoming Statewide Framework Water Plan aquifer classification system (WWC Engineering, Inc. and others, 2007), and the hydrogeology presented in this study are explained on the hydrostratigraphic charts found on **Plates J, K, M, S, T,** and **U** and **Figure 7-2.**

5.4 Influence of structure on groundwater circulation

Huntoon (1993) presented a summarized conceptual model for "The Influence of Laramide

Foreland Structure on Modern Ground-water 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. The central thesis of their research 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 major Paleozoic and lower Mesozoic major carbonate aquifers exposed along the major uplifts of the Wyoming foreland basins. The main components of this conceptual model include:

- The 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 cross sections shown in **Figures 4-7, 4-10** and **4-15** provide good examples of this typical Laramide structural pattern, particularly the fault-severed strata. The cross sections shown in **Figures 4-11, 4-12, 4-13** and **4-14** present views of Laramide basin architecture along the homoclinal west side of the Laramie Mountains especially the upland exposure and basinward dip and burial of the major carbonate aquifers.
- 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 foreland structural basins.
- Groundwater circulation is not only controlled by the Laramide structures, but also alters the hydrogeology of them:
    - Fracture (secondary) permeability within carbonate strata associated with faulting and folding has been enhanced by carbonate dissolution.
    - Any fracture can potentially enhance permeability, even if formed in a compressional environment (e.g., trough of a synclinal fold).
    - 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 solution-enhanced, highly anisotropic permeability. Where it develops, extensional fracture 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 along and parallel or oblique to the folds.
    - Large-displacement thrust faults and smaller displacement 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 the hanging wall and the footwall of major uplift-bounding, large-displacement faults.
    - Within synclinal folds the rocks are highly compressed, out-of-synclinal thrusting thins the strata, interstitial porosity is destroyed, and fractures are compressed rather than open.
    - Faults can act as either conduits or barriers to flow.

- 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.

- Where permeability is not enhanced by solution-enlarged fractures, which includes by far most of the subsurface extent of the major carbonate aquifers, intercrystalline permeability is very low.
- Groundwater circulation is primarily parallel to 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 plastic, 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 the deeper major carbonate aquifers are exposed at generally higher elevations in the surrounding mountain ranges.
- Large production from the 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 the carbonate aquifers become covered by a significant confining unit. 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 water 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.
- The synclinal areas of folds 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 the Wyoming 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 been utilized in groundwater development projects throughout the state. **Appendix B** lists Wyoming Water Development projects that have implemented this exploration model. Clearly, identifying and mapping structures in groundwater prospects in the major carbonate aquifers and other aquifers considered for high yield groundwater development would be an important aspect of any groundwater exploration project in the Platte River Basin. Groundwater circulation in the major carbonate aquifer systems of the Platte River Basin is discussed further in **Chapter 7**. Several of the components of the conceptual model described above are illustrated in **Figure 5-1**.

5.5 Conceptual models of deep basin groundwater flow

The fate of groundwater that flows downgradient of its aquifer outcrops and into the deeper parts of a structural basin is not well understood. Several conceptual models have been developed over the past four decades to explain deep groundwater circulation in the typical Rocky Mountain Laramide Basin. Richter (1981a, p. 83, Figure V-3) proposed that within all basin aquifers, down to the surface of the Precambrian basement, small flows continued from outcrop areas on the basin flanks to the center of the basin and thence upward toward ground surface, in response to the strong vertical gradient that develops with progressive downgradient flow into the basin.

In contrast, oil and gas geologists and engineers have developed several generally similar exploration models, variously referred to as "Basin Centered Gas Systems" (BCGS), "Deep Basin Gas Systems," "Tight Gas Systems," and "Continuous Gas Systems," to name a few of the most popular (Shanley and others, 2004), that would preclude Richter's (1981a) groundwater-flow model.

5.5.1 Implications of the basin centered gas systems exploration model for deep-basin groundwater resource potential

The relevant hydrogeologic aspect of BCGS models is that the deeper volumes of Rocky Mountain Laramide basins (and other basins worldwide) are characterized by multi-phase fluid-flow systems of water, liquid hydrocarbons, and natural gas; with the gas phase typically anomalously pressured relative to hydrostatic pressure. Within these multi-phase flow systems, the formation's permeability to water (generally brine) decreases as the proportion of gas and liquid hydrocarbon phases increase to the extent that groundwater essentially will not flow. This condition, commonly referred to as "irreducible water saturation," is consistent with the very low water production rates typically observed by oil and gas producers from BCGS reservoirs, especially fine-grained reservoirs. Within BCGSs, groundwater can be essentially immobile over a wide range of conditions even where it is a significant fraction of the fluid occupying the pore space, especially in low-permeability rocks. In multi-phase flow systems, permeability relationships are complex and generally lower for all fluids in proportion to their percent saturation of the total fluid. Heterogeneous lithology is commonly associated with patchy saturation.

Surdam and others (2005) summarizes the BCGS conceptual model and the following characteristics common to these hydrocarbon systems:

- Anomalously pressured (both high and low) compartmentalized BCGS reservoirs are separated from the overlying normally (hydrostatic) pressured, single-phase, meteoric groundwater-flow system by a regional pressure surface boundary.
- There is a significant change in water chemistry and thermal regime across the pressure surface boundary; below the surface, meteoric flow is precluded, water quality declines toward brine composition, and temperature increases along the geothermal gradient. Higher temperatures enable increased dissolution of rock matrix minerals and lower water quality.

- Capillary displacement pressure increases by several orders of magnitude below the surface, especially within fine-grained strata. Increased displacement pressure significantly reduces groundwater flow across the surface, essentially isolating the two flow regimes. The resulting compartmentalization forms isolated flow systems below the surface.

The pressure surface boundary in Rocky Mountain Laramide basins is generally encountered at approximately 8,000 feet, but can vary by thousands of feet of relief related to the formation of “gas chimneys,” the presence of large-scale structures, and stratigraphy. Although poor water quality and high drilling costs generally limit groundwater development to depths much less than 8,000 feet, it is clear that under the BCGS model, except for brine production, the development of deep-basin (below the pressure surface) groundwater resources (unrelated to mineral production) is not feasible. In addition, circulation within the interval from above the surface to current groundwater development depths would be complicated by high relief on the boundary surface, and development would generally be impractical. In many cases BCGSs have a base above the Precambrian basement, and the interval between the BCGS and basement is normally pressured. Although it is possible that meteoric water circulates to great depth in these areas, the depth, temperature, low permeability (from compaction) and poor water quality would preclude groundwater development.

5.5.2 Deep-basin groundwater resource development

In actuality, it may make little difference whether deep groundwater circulation is better described by the BCGS or Richter model because the volumes entering the deep parts of a Laramide basin may be quite small. Huntoon (1983a, b. c) noted that flows into the deep basin constitute only small fractions of the recharge received over basin margin outcrops due to basinward decreases in aquifer permeabilities; the largest part of recharge is rejected as discharge from springs located near the contact of the aquifer outcrop (recharge area) and the overlying confining unit. This hypothesis is supported by numerical simulation models used to study regional flow in other structural basins.

A groundwater flow model developed by Belitz and Bredehoeft (1988) calculated that only 64 cfs (46,000 acre-feet) move into the basin deeps of the 200,000 mi^2 regional flow system comprised of the Denver-Julesburg Basin and its associated uplifts. A similar model developed by Downey (1982) estimated deep basin flows of 77 cfs for the 300,000 mi^2 regional aquifer that includes the Williston Basin of North Dakota. If the low flow rates calculated for these large basins are generally characteristic of Laramide basins, then proportionate deep basin regional flows in the 26,289 mi^2 Platte River Basin would be quite small and preclude groundwater development at production rates sufficient to justify the costs of deep basin drilling and production. Furthermore, the rapid degradation of water quality observed in deep basin aquifers would require treatment to make deep groundwater resources potable.

In summary, none of the conceptual models of deep groundwater circulation, discussed above, preclude the evaluation of Platte River Basin groundwater resources based on the recharge and water balance **(Chapters 6 and 8)** approach used in this study, especially in light of the limited amount of data available relative to the size and diversity of the Platte River Basin hydrogeologic system. However, the possibility that deep basin flows could be quite small should lead groundwater professionals to reconsider the concept of safe yield with respect to the effects that further groundwater development may have on surface water flows and water rights holders.

5.6 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 are primarily dependent on water quality. Groundwater quality data for the Platte River Basin hydrogeologic units **(Section 5.6)**, was compiled for this study by the USGS from several sources. The data confirms that the best quality groundwater is generally found in regions that are closest to recharge areas, and that quality is affected by chemical reactions that occur during infiltration through the vadose zone and circulation through the aquifer. Factors that affect groundwater quality include the types 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 Platte River Basin than to the "major aquifers," within which groundwater circulation is often substantially more vigorous. Groundwater quality in the Platte River Basin varies from fresh, with total dissolved solids (TDS) less than 1,000 mg/l, suitable for any domestic purpose, to briny, unsuitable for virtually any use, with TDS greater than 200,000 mg/l from deep oil field aquifers.

In the absence of irrigation, most alluvial aquifers receive recharge from hydrologically connected streams and underlying and adjacent bedrock formations. Irrigation can dominate recharge when application is active. Direct precipitation can also add to recharge, but due to high evapotranspiration rates in the basin interiors, 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 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 when recharge is 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 salt. 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 Platte 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 chloride is dominant 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.

Sections 5.6.1.1 – 5.6.1.5 contain 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 Platte River Basin aquifers and their component geologic and lithostratigraphic units is provided in **Chapter 7**.

5.6.1 Groundwater quality

This section of the report describes regulation and classification of groundwater in Wyoming; groundwater-quality standards used in this report for descriptive purposes; and how data on chemical characteristics of hydrogeologic units in the Platte River Basin groundwater study were accessed, compiled, screened, and statistically summarized.

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, Colorado, regulates the public water systems located within Wyoming. Each agency has established groundwater standards, and revises and updates them from time to time.

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* (Wyoming Department of Environmental Quality, 1993), 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 treatment.
- <u>Class IV(B) Groundwater of the State</u> – Groundwater that has a TDS concentration in excess of 10,000 mg/L.
- <u>Class V Groundwater of the State</u> – 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).
- <u>Class VI Groundwater of the State</u> – Groundwater that may be unusable or unsuitable for use.

5.6.1.1 Standards of groundwater quality

Groundwater quality is compared to four types of USEPA standards: Maximum Contaminant Level (MCL), Action Level (AL), Secondary Maximum Contaminant Level (SMCL), and Lifetime Health Advisory Level (LHA) standards. In assessing suitability for domestic use (Wyoming Class I groundwater), USEPA health-based Maximum Contaminant Level (MCL), Action Level (AL), Secondary Maximum Contaminant Level (SMCL), and Lifetime Health Advisory Level (HAL) standards are used (even though they are not legally enforceable for any of the sampling sites used in this study) (**Table 5-2**). The USEPA MCLs (U.S. Environmental Protection Agency, 2011) 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. MCLs do not apply to groundwater for livestock, irrigation, or self-supplied domestic use. They are, however, a valuable reference when assessing the suitability of water for these uses. An AL is the concentration of the chemical, which, if exceeded, requires treatment by the public water supplier (U.S. Environmental Protection Agency, 2011). USEPA SMCLs (U.S. Environmental Protection Agency, 2011) 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. USEPA Health Advisory Levels are nonenforceable standards that establish acceptable constituent concentrations for different exposure periods. In this study, concentrations are compared with the lifetime Health Advisory Level (HAL), which is the concentration of a chemical that would not result in any known or anticipated adverse noncarcinogenic health effects over a lifetime of exposure (70 years) (U.S. Environmental Protection Agency, 2011).

Quality standards for Wyoming Class II, Class III, and Class IV groundwater (Wyoming

Table 5-2. Selected groundwater quality standards and advisories.

Physical characteristics and constituents		Groundwater quality and standards: Domestic [1] MCL or AL (USEPA)	Domestic [1] SMCL (USEPA)	Domestic [1] HAL (USEPA)	Agricultural[2] Class II (WDEQ/WQD)	Livestock[2] Class III (WDEQ/WQD)
Physical characteristics	pH (standard units)		6.5-8.5		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
	SAR (ratio)				8	
Trace elements (µg/L)	aluminum (Al)		50-200		5,000	5,000
	antimony (Sb)	6				
	arsenic (As)	10			100	200
	barium (B)	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)	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 USEPA 2011 edition of the Drinking Water Standards and Health Advisories (U.S. Environmental Protection Agency, 2011)

[2] Selected from WDEQ, 1993 [revised 2005], Water Quality Rules and Regulations, Chapter 8, Quality Standards for Wyoming Groundwaters, 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 pCi/L standard is a proposed MCL, whereas the 4,000 pCi/L standard is a proposed alternative MCL for communities with indoor air multimedia mitigation programs (U.S. Environmental Protection Agency, 1999).

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 use. Class IV groundwater is water that is suitable for industry. The Class IV standard is a TDS-only standard (10,000 mg/L) that 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.

5.6.1.2 Sources, screening, and selection of data

Groundwater-quality data were gathered from for 1911-2010 the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2010a), the USGS Produced Waters Database (PWD) (U.S. Geological Survey, 2010b), the Wyoming Oil and Gas Conservation Commission (WOGCC) database (Wyoming Oil and Gas Conservation Commission, 2010), the University of Wyoming Water Resources Data System (WRDS) database, 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. For some constituent results, zero values were present in the original data set. During sample evaluation, we inferred that these values should have been reported as missing or as censored values. Because a censoring limit was not stored with the historical samples, the zero values were removed from the data sets.

Groundwater-quality data were gathered from the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2010a), the USGS Produced Waters Database (PWD) (U.S. Geological Survey, 2010b), the Wyoming Oil and Gas Conservation Commission (WOGCC) database (Wyoming Oil and Gas Conservation Commission, 2010), the University of Wyoming Water Resources Data System (WRDS) database, 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 that monitor known or potential point-source contamination sites or mining spoils sites. For some constituent results, zero values were present in the original data set. During sample evaluation, we inferred that these values should have been reported as missing or as censored values. Because a censoring limit was not stored with the historical samples, the zero values were removed from the data sets.

Many of the Platte River Basin groundwater sites 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. An exception involved some sets of PWD samples from the same well at different depths and from different hydrogeologic units. 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 data set.

Groundwater-quality sample analyses from the USGS PWD (U.S. Geological Survey, 2010b) are used in this report. Produced water is water co-produced with oil and gas. The PWD includes samples within the Platte River Basin. Only those PWD samples from a wellhead or from a drill-stem test were used. Samples not assigned to a hydrogeologic unit were removed from the data set. 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. PWD documentation (U.S. Geological Survey, 2010b) 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 (U.S. Geological Survey, 2010b), some sample analyses may have reported the sum of sodium and potassium concentrations as sodium concentration alone.

Groundwater-quality sample analyses from the WOGCC database are used in this report. Major-ion balances were calculated for these samples. Samples with an ion balance of greater than 10 percent generally were removed, but some samples with an ion balance of between 10 and 15 percent from areas with few samples were retained.

Some groundwater-quality samples from the WRDS database are used in this report. Samples from wells and springs where information was not available to identify the hydrogeologic unit or the site was not in the USGS NWIS database were removed from the WRDS data set. In addition, WDEQ monitoring wells located at sites of known or potential groundwater contamination were removed 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 data set.

Groundwater quality in the Platte 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 areas increases (and residence time increases). Correspondingly, the water quality in a given hydrogeologic unit generally deteriorates with depth.

Many of the groundwater-quality samples from Quaternary and Tertiary hydrogeologic units came from wells and springs that supply 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, that unit generally is not used for water supply if a shallower supply is available. For these reasons, the groundwater-quality samples from the Quaternary, Tertiary, and some Cretaceous hydrogeologic units are most likely 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.

Many of the groundwater-quality samples used in this study to characterize Mesozoic and Paleozoic hydrogeologic units are produced-water samples from the USGS PWD and WOGCC databases. Although these samples were from oil and gas production areas, we believe that they may have less bias in representing ambient groundwater quality than samples used to characterize Quaternary and Tertiary hydrogeologic units.

5.6.1.3 Water-quality characteristics

The TDS concentration in groundwater tends to be high with respect to the USEPA SMCL in most of the Platte 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 can adversely affect crop production. High TDS concentrations also cause scale build-up in pipes and boilers. No USEPA MCL is available for TDS, and the USEPA SMCL for TDS is 500 milligrams per liter (mg/L) (U.S. Environmental Protection Agency, 2011). 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 predict sodium replacing adsorbed calcium and magnesium in soil, which damages soil structure and reduces permeability of the soil to water infiltration (Hem, 1985). The SAR should be used in conjunction with information about the soil characteristics and irrigation practices in the area being examined. The high SAR (greater than 8) of waters in some hydrogeologic units in the Platte River Basin indicates that these waters may not be suitable for irrigation.

Many groundwater-quality samples reviewed for this report also contain high concentrations of sulfate, chloride, fluoride, iron, and manganese, with respect to USEPA and WDEQ water-quality standards. As expected, produced water (defined in the produced-water sample section, below) commonly exceeded many USEPA and WDEQ standards.

Sulfate in drinking water can adversely affect the taste and odor of the water, and may cause diarrhea (U.S. Environmental Protection Agency, 2011). The USEPA SMCL for sulfate is 250 mg/L (U.S. Environmental Protection Agency, 2011), the WDEQ Class II groundwater (agricultural) standard is 200 mg/L, and the WDEQ Class III groundwater (livestock) standard is 3,000 mg/L.

A high chloride concentration can adversely affect the taste of drinking water, increase the corrosiveness of water, and damage salt-sensitive crops. The USEPA SMCL for chloride is 250 mg/L (U.S. Environmental Protection Agency, 2011), the WDEQ Class II groundwater (agricultural) standard is 100 mg/L, and the WDEQ Class III groundwater (livestock) standard is 2,000 mg/L.

High fluoride concentrations commonly are associated with produced water from deep hydrogeologic units in sedimentary structural basins. 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, 2011). 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 of plumbing fixtures. The USEPA has established SMCLs for iron at 300 micrograms per liter (µg/L) and manganese at 50 µg/L (U.S. Environmental Protection Agency, 2011). High concentrations of iron and manganese in irrigation water may have a detrimental effect on crop production (Bohn and others, 1985, and references therein).

5.6.1.4 Statistical analysis

In relation to groundwater quality, analysis has two meanings in this chapter, *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 per liter* (6 milligrams of calcium per liter of water). The chemical analysis may include such physical measurements of chemical characteristics as pH (a measure of hydrogen ion activity). The statistical analysis of a *set* of chemical analyses is the mathematical treatment of the set of data to describe and summarize those data in order to convey certain useful descriptive characteristics: for example, *the calcium concentration in groundwater samples from this formation 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 we used to compile, analyze, and present water-quality data for samples of groundwater from the Platte River Basin. Supplementary data tables contain all the data used in this chapter—data too numerous for inclusion in the chapter, but available online at (WSGS to eventually add URL here). From these data, we derived *summary statistics* for physical characteristics and chemical quality of groundwater in Platte River Basin hydrogeologic units, as tabulated in **Appendix E** for environmental samples and **Appendix F** for produced-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 (pumped out of the ground) with oil and gas. We also used these data to compare groundwater quality in Platte River Basin hydrogeologic units to USEPA and WDEQ standards for various 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 (**Appendices E** and **F**). Standard summary statistics also were included for iron concentrations from produced waters. Censored data are data reported as above or below some threshold, such as "below detection limit" or "less than 1 mg/L." For a very small number of major-ion samples, censored values ("less-than") may have been reported for a major-ion constituent. These censored values were treated as uncensored values at the laboratory reporting limit, level for statistical analysis. For uncensored data sets with a sample size of 1, only a minimum value is reported in **Appendices E** and **F**; 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.

Many nutrient concentrations, trace element concentrations, and radiochemical concentrations were reported as censored values in the environmental waters data set. In some cases, censored values 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 must be 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 data set; therefore, the summary statistics presented in the report for nutrients, trace elements, and radiochemical constituents are the 25th percentile, median, 75th percentile, and maximum. For some constituents and hydrogeologic units, water-quality data could not meet the minimum sample size or uncensored value requirements for the AMLE technique. For constituents within a hydrogeologic unit that had a sample size of 1, a minimum value is reported, and for a sample size of 2, minimum and maximum values are reported. In those instances where the sample size was three or greater, but the number of uncensored values was too small, the AMLE technique failed to compute percentiles; therefore, summary statistics are not presented in **Appendix E**. In those cases, although a data set for a constituent and hydrogeologic unit was insufficient for determining summary statistics with the AMLE technique, individual samples could still be used for groundwater-quality exceedance analysis.

Groundwater-quality standard exceedance frequencies are described for domestic, irrigation, and livestock use, on the basis of USEPA and WDEQ standards. Groundwater-quality standard exceedance frequencies were calculated and reported as a percentage for a hydrogeologic unit. When only one sample exceeded a standard, the text indicates one sample exceeded a standard, rather than indicating '100 percent'. Groundwater-quality standard exceedance frequencies were determined using the filtered analyses for a constituent because filtered analyses were more commonly (or frequently the only) analyses available. Only samples for a constituent that were analyzed at a censoring 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 there were five samples 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 can be compared to the SMCL of 50 μg/L for manganese. The sample with the value of <100 μg/L cannot 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 50 percent of samples exceeded the SMCL of 50 μg/L. Manganese would not be included in the appendix for the hydrogeologic unit in this example because values were too censored for the AMLE technique to calculate summary statistics. The AMLE technique criterion of having three uncensored values in the data set was not met. Descriptions of the constituents that were included in the statistical summaries for environmental water samples and produced-water samples are summarized in the next section.

5.6.1.4.1 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 (U.S. Geological Survey, 2010), the WRDS database, and other sources such as consulting engineers' reports related to water-supply exploration and development. Physical characteristics, major-ion chemistry, nutrients, trace elements, and radiochemicals are summarized for environmental waters.

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

Major-ion chemistry of environmental waters, comprising major ions and associated characteristics or constituents, was reported as laboratory analyses of filtered waters (or constituents were calculated from laboratory analyses). Major-ion constituents and related characteristics include hardness (calculated and reported as calcium carbonate), dissolved calcium, dissolved magnesium, dissolved potassium, sodium-adsorption ratio (calculated), dissolved sodium, alkalinity (reported as calcium carbonate), dissolved bromide, dissolved chloride, dissolved fluoride, dissolved silica, dissolved sulfate, and total dissolved solids (TDS). These constituents are reported in milligrams per liter, and with the exception of TDS, the term "dissolved" is not used for the major ion constituents analyzed in filtered water samples hereafter in this report.

For this report, a measured laboratory value of TDS (residue on evaporation at 180 degrees Celsius) was commonly used. 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 used. 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 value of alkalinity was used; and if that was not available, an unfiltered field ANC value was used to report alkalinity.

Nutrient constituents in environmental waters, analyzed in a laboratory using filtered waters, include dissolved ammonia (reported as nitrogen), dissolved nitrate plus nitrite (reported as nitrogen), dissolved nitrate (reported as nitrogen), dissolved nitrite (reported as nitrogen), dissolved organic carbon, dissolved orthophosphate (reported as phosphorus), and dissolved phosphorus (reported as phosphorus). In addition, nutrient constituents analyzed in a laboratory using unfiltered waters that were included in the summary statistics are ammonia (reported as nitrogen), ammonia plus organic nitrogen (reported as nitrogen), nitrate (reported as nitrogen), nitrate plus nitrite (reported as nitrogen), nitrite (reported as nitrogen), organic nitrogen (reported as nitrogen), total nitrogen (reported as nitrogen), organic carbon, and total phosphorus (reported as phosphorus). Separate summary statistics were calculated for each constituent and phase that was analyzed. The term dissolved is not used for nutrient constituents analyzed in filtered water samples hereafter in this report. The term 'unfiltered' is used with constituents that were analyzed from unfiltered water hereafter in this report. These constituents are reported in milligrams per liter.

Trace element constituents in environmental waters, analyzed in a laboratory using filtered waters, include dissolved constituents of 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 analysis. Separate summary statistics were calculated for each constituent and phase that was analyzed. The term dissolved is not used for trace element constituents analyzed in filtered water samples hereafter in this report. The term 'unfiltered' is used with constituents that were analyzed from unfiltered water hereafter in this report. These constituents are reported in micrograms per liter.

Radiochemical constituents in environmental waters, analyzed in a laboratory using filtered waters, include dissolved alpha radioactivity (using thorium-230 curve or natural uranium curve method), gross beta radioactivity, dissolved radium-226 (using an unspecified or a radon method), dissolved radium-228, and dissolved uranium (natural); the term "dissolved" is not used for the radiochemical constituents analyzed in filtered water samples hereafter in this report. In addition, radon-222 (unfiltered) (referred to herein as "radon") and tritium (unfiltered) were included in the analysis. All radiochemical constituents are reported in picocuries per liter except uranium, which is reported as micrograms per liter.

5.6.1.4.2 Produced-water samples

Produced-water samples are from wells related to natural resource exploration and extraction (primarily oil and gas production). Produced-water data were compiled from the WOGCC database, the USGS PWD, and the other sources listed under *environmental water samples*. Physical characteristics, major-ion chemistry, and the trace elements are summarized for produced waters. Nutrients and radiochemical data were not included in the statistical analysis because they were reported with the chemical analyses of just a few isolated samples.

Physical characteristics, major-ion chemistry, and trace elements summarized for produced waters were generally the same as for environmental waters, with some exceptions. In the produced-waters data set, the water phase (filtered or unfiltered) was not reported with the data. For physical characteristics, only pH (in standard units) was statistically analyzed. The source (laboratory or field) of the pH values was unknown. Major-ion chemistry constituents and related characteristics statistically analyzed are calcium, magnesium, potassium, sodium, bicarbonate (reported as bicarbonate), carbonate (reported as carbonate), chloride, sulfate, and total dissolved solids. The method for determining total dissolved solids was not reported with the data. The reporting unit for major-ion chemistry was milligrams per liter. For trace elements, iron was the only constituent that was routinely analyzed in samples. Other trace elements were analyzed in just a few isolated samples and thus were not statistically analyzed. Iron concentrations in the original data set were reported in milligrams per liter; we converted them to micrograms per liter for the statistical summary.

5.6.1.5 Trilinear diagrams

The relative ionic composition of groundwater samples from springs and wells in the Platte River Basin study area are plotted on trilinear diagrams (**Appendices G and H**). 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 G and H**). 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).

5.7 Aquifer sensitivity and potential groundwater contaminant sources

This report provides an evaluation of the types of contamination that potentially threaten groundwater resources in the Platte River Basin. It is axiomatic that protecting groundwater from contamination is much more rational and attainable than cleaning it up after it has been impacted through 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, Region VIII (EPA) 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 by the Spatial Data and Visualization Center (SDVC) of the *Wyoming Groundwater Vulnerability Assessment Handbook* (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 and this present study. 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 map products from the 1998 SDVC study are used to evaluate the potential for groundwater contamination in the Platte River Basin: 1) a map of average annual recharge **(Figure 5-2)** and 2) a map of aquifer sensitivity **(Figure 5-3)**. **Figures 5-4** through **5-10** are maps of potential groundwater contaminant sources in the Platte River Basin. Additional discussion on the rationale for and methodology used in developing **Figures 5-1** through **5-10** is provided in **Appendix C**.

5.7.1 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:

- <u>Aquifer sensitivity</u> 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."*
- <u>Groundwater vulnerability</u> 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

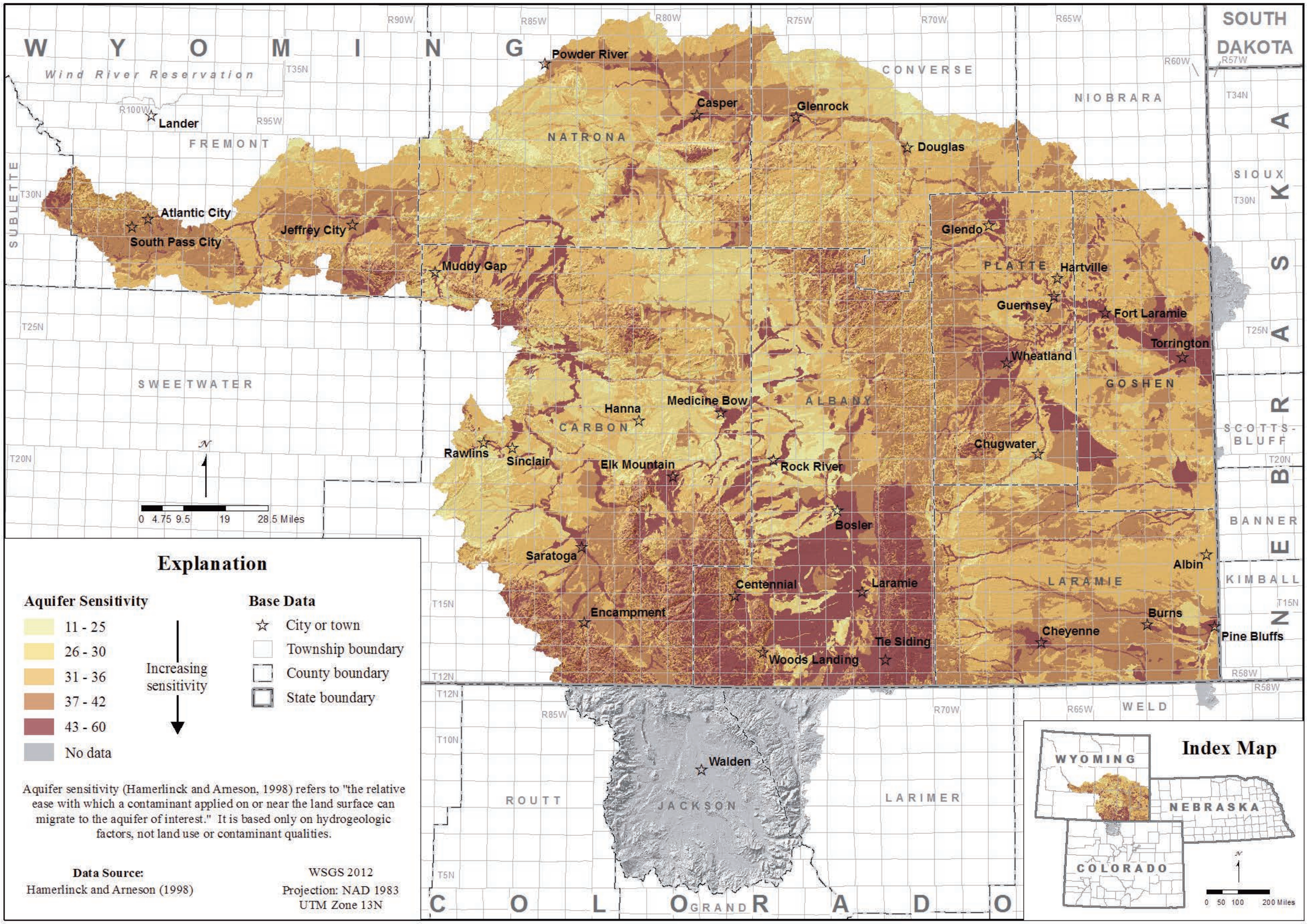

Figure 5-3. Aquifer sensitivity, Platte River Basin, Wyoming.

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 **(Figure 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 (EPA, 1993) based on six independent parameters:

- Depth to initial groundwater.
- Geohydrologic setting.
- Soil media.
- Aquifer recharge (average annual).
- Topography (slope).
- 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 Platte 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 **(43-60)** are located primarily over interior basin alluvial deposits, adjacent to rivers, streams, and lakes, and in the highly fractured mountainous 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 them 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 Platte River Basin. These areas generally have relatively thicker, well-drained, mature soils, rolling topography with minor relief (lower slopes), and generally 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 **(11-25)** 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, very low average precipitation, or both.

5.7.2 Potential sources of groundwater contamination

Figures 5-4 through **5-10** illustrate potential groundwater contaminant sources in the Platte River Basin. These generally include industrial, retail, private, and public facilities that manufacture, process, use, store, sell, dispose, or otherwise handle substantial volumes of products, wastes, and other substances with physical and

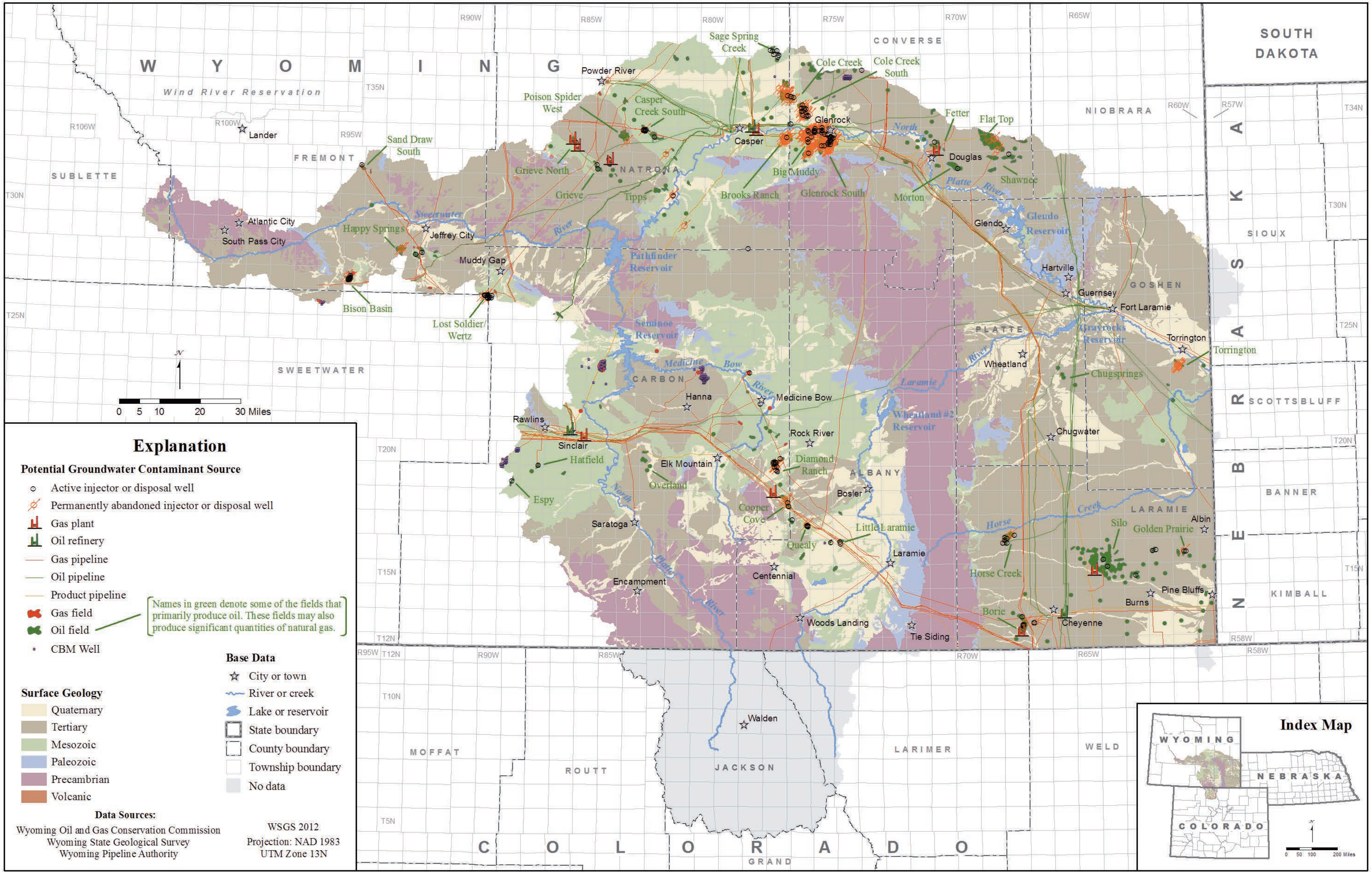

Figure 5-4. Potential groundwater contaminant sources: oil and gas fields, pipelines, refineries, and Class II injection and disposal wells, Platte River Basin, Wyoming.

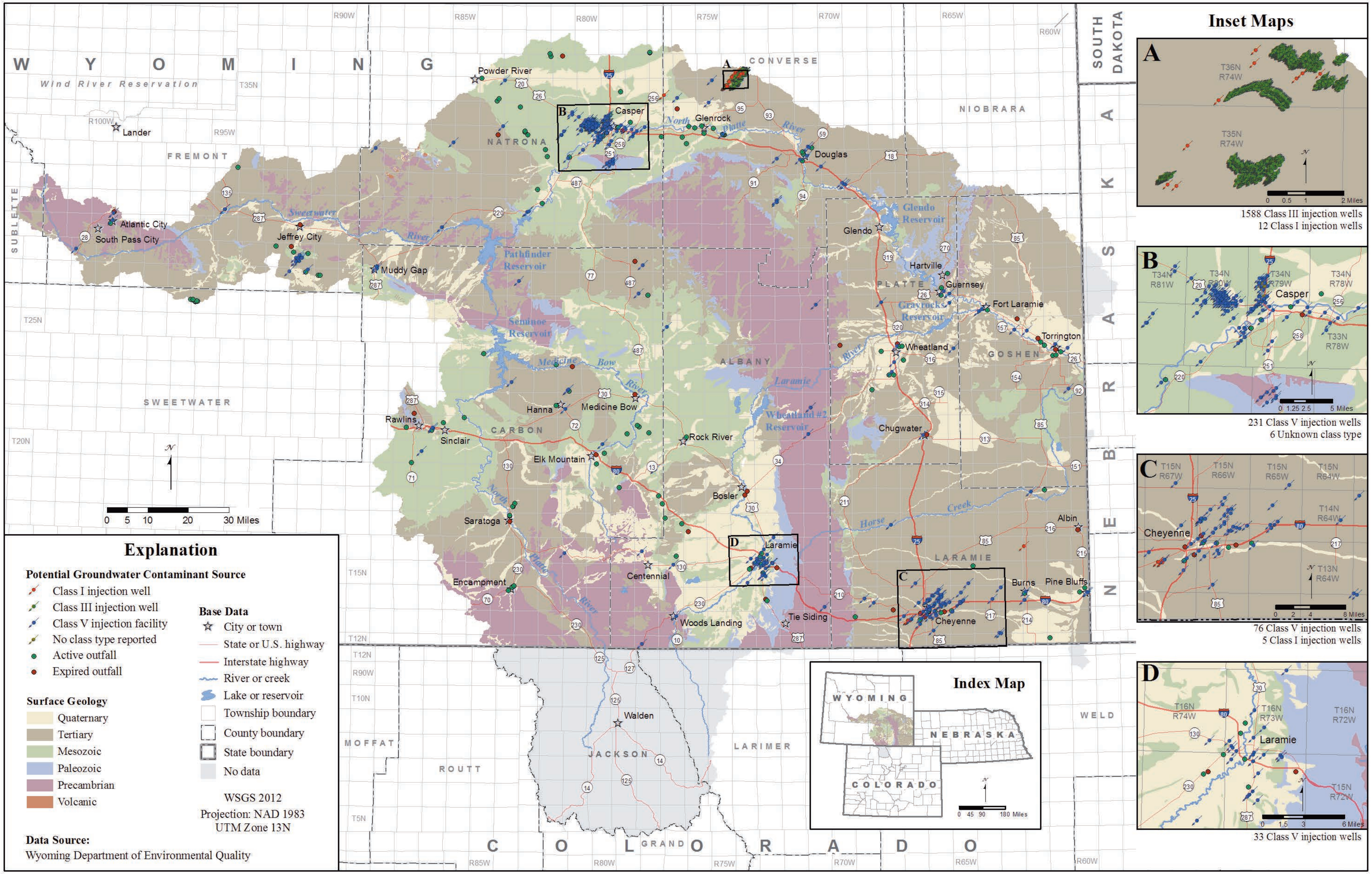

Figure 5-5. Potential groundwater contaminant sources: Class I, III, and V injection wells permitted through the Wyoming Department of Environmental Quality Underground Injection Control (UIC) program, and active and expired outfalls in the Wyoming Pollutant Discharge Elimination System (WYPDES) program, Platte River Basin, Wyoming.

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 water-table aquifers and the outcrop/recharge areas of commonly confined aquifers. **Figure 5-3** shows areas where migration to the water table is most likely.

The identification and mapping of facilities as potential sources of groundwater contamination ***does not*** imply that they are impacting groundwater resources; however, contamination has been confirmed at specific facilities throughout the state. Generally, these facilities are strictly regulated by one or more government agencies 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:

- 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 (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).
- Underground coal gasification sites.

WDEQ Solid and Hazardous Waste Division:

- Known contaminated sites regulated under the Voluntary Remediation Program (VRP), including orphan sites and brownfield assistance sites.
- Permitted disposal pits and other small treatment, storage, and disposal (TSD) facilities.
- Landfills.
- 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.
- Produced water pits.

Wyoming State Geological Survey:

- Oil and gas fields, plants, compressor stations.
- Pipelines.
- Mines (active and inactive).
- Gravel pits, quarries, etc.

The agencies, listed above, 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 **(Plate 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

- **Oil and gas fields:** Oil and gas exploration, production, processing, and transportation facilities handle large volumes of petroleum hydrocarbons, produced water, and

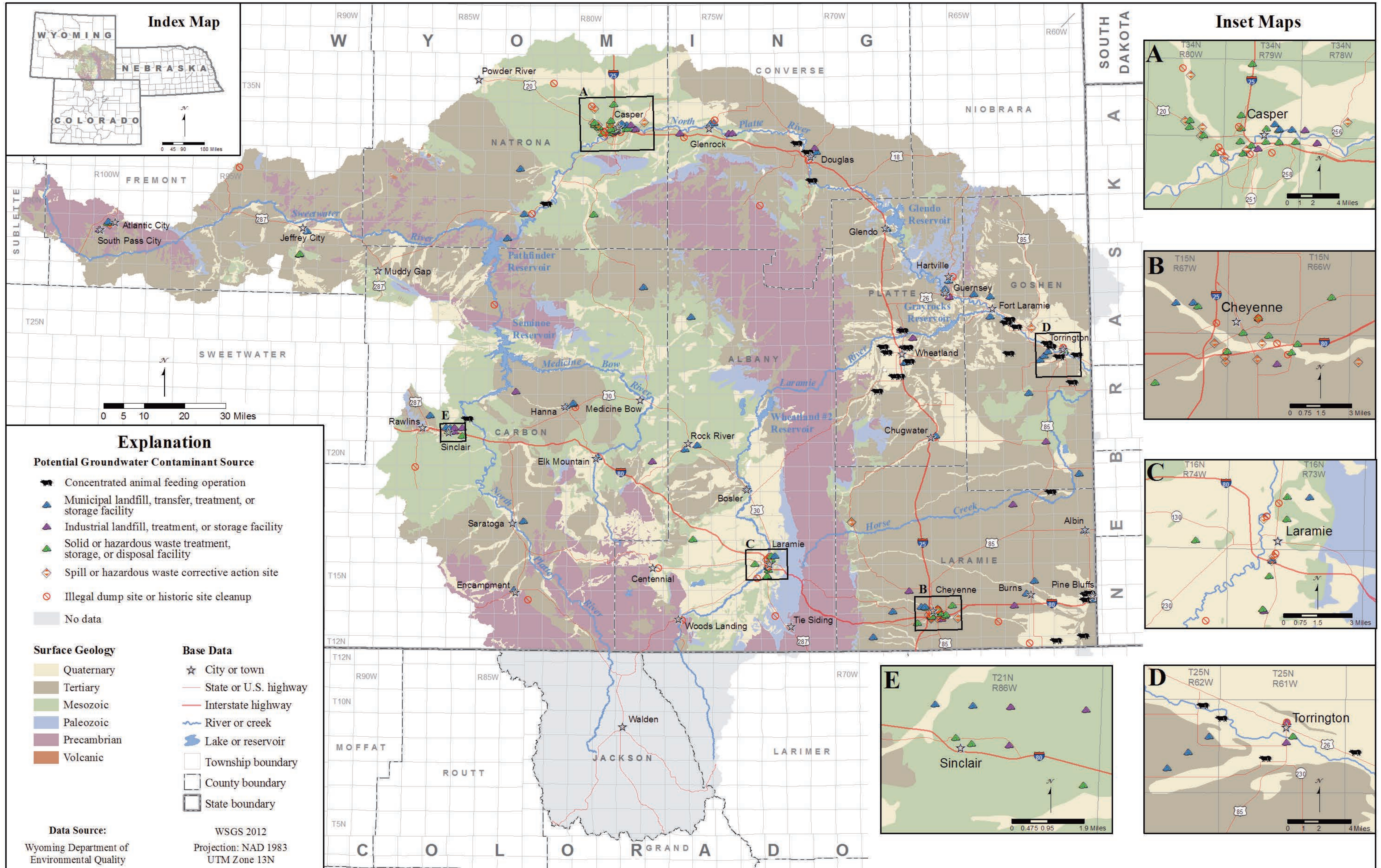

Figure 5-6. Potential groundwater contaminant sources: Wyoming Department of Environmental Quality permitted and inventoried solid and hazardous waste facilities, and concentrated animal feeding operations (CAFOs), Platte River Basin, Wyoming.

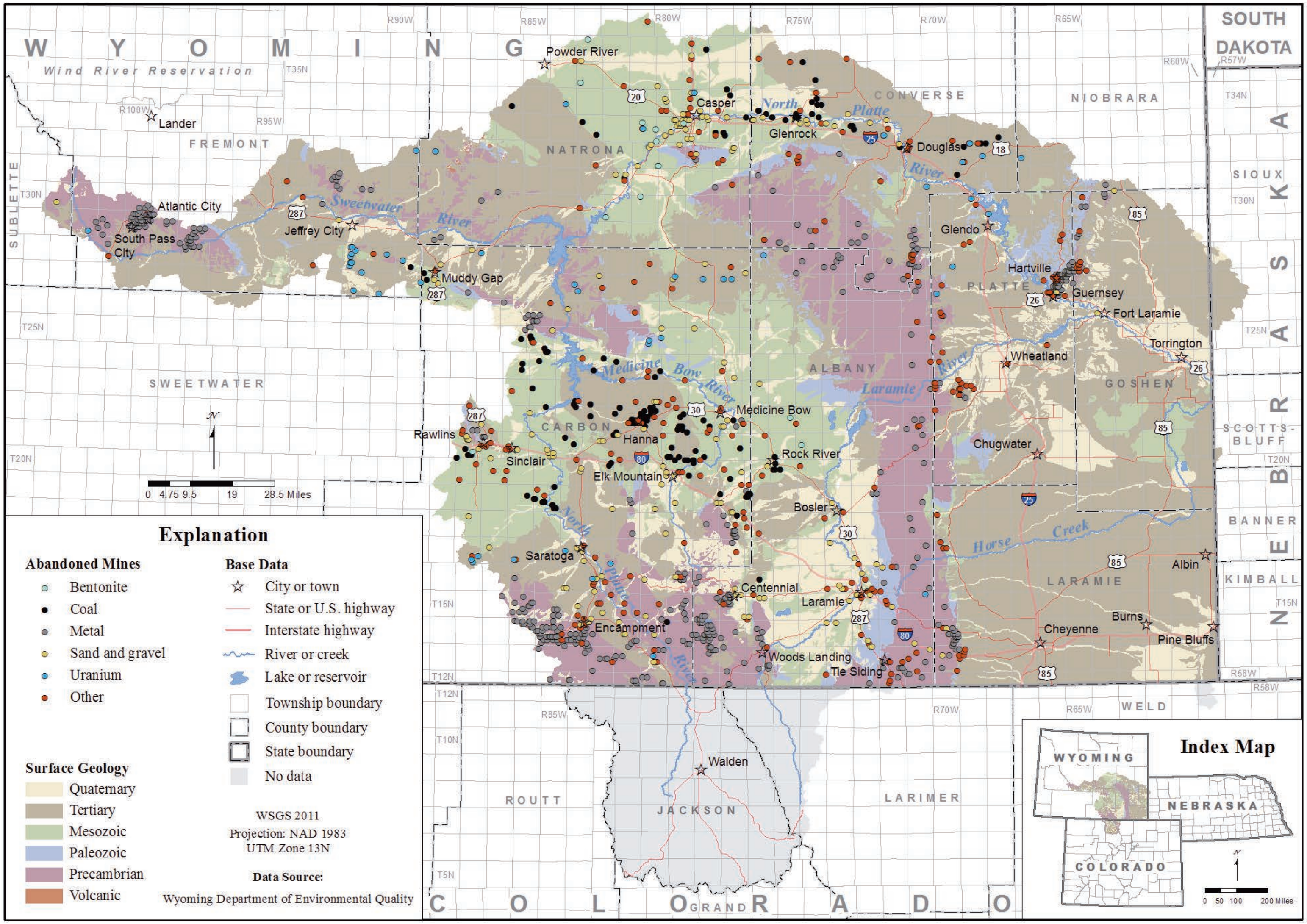

Figure 5-7. Potential groundwater contaminant sources: Wyoming Department of Environmental Quality Abandoned Mine Land Division abandoned mine sites, Platte River Basin, Wyoming.

substantial volumes of other products that can pose a threat to groundwater such as fuel, methanol, glycols, amines, lubrication and hydraulic oils, acids, and a variety of well hydraulic fracturing and treatment chemicals. Large volumes of waste and wastewater are typically generated by oil and gas operations. Releases can occur from storage tanks, process vessels, and above-ground and underground piping. In some cases hydrocarbons, produced water, and other chemicals are discharged to pits constructed for a wide variety of applications. Older and abandoned pits were commonly unlined and; therefore, have greater potential for groundwater contamination. Notably, the historic storage and disposal of relatively mobile natural gas condensate in unlined pits has resulted in confirmed shallow groundwater contamination at several locations in the Platte River Basin. Prevention and mitigation of groundwater contamination resulting from releases of petroleum hydrocarbons is a primary area of concern and regulation by local, state, and federal agencies.

- **Pipelines:** Interstate 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 and release substantial volumes of contaminants.
- **Active and permanently abandoned injector and disposal wells:** Injector wells are permitted by the WOGCC for injecting produced water into permeable zones that are deeper than and hydraulically isolated from useable groundwater resources for disposal, for maintaining reservoir pressure for enhanced oil recovery, and other purposes. Injector wells are mapped as potential contaminant sources because there are several in the Platte River Basin and because they typically inject large volumes of produced water that could pollute groundwater resources if leaked into shallower aquifers. Injection facilities also employ bulk storage tanks, piping systems, and other equipment that can release produced water or other contaminants in recharge areas. Class II wells are strictly regulated by the WOGCC and the BLM/EPA and 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.

Figure 5-5 – Potential groundwater contaminant sources: Class I and V injection wells in the WDEQ UIC Program, and active and expired outfalls in the WDEQ WYPDES 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 (RCRA definition) into hydraulically isolated, permeable zones that are deeper than, and isolated from, useable groundwater resources. Produced water disposal makes up a large component of injected fluids. Class I wells are strictly regulated and generally have minimal potential for impacting groundwater resources. Class I wells are mapped because of the wider range of liquid wastes they are allowed to accept for injection. In contrast, Class V facilities are used to 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 3 Class V facilities, permitted to inject industrial

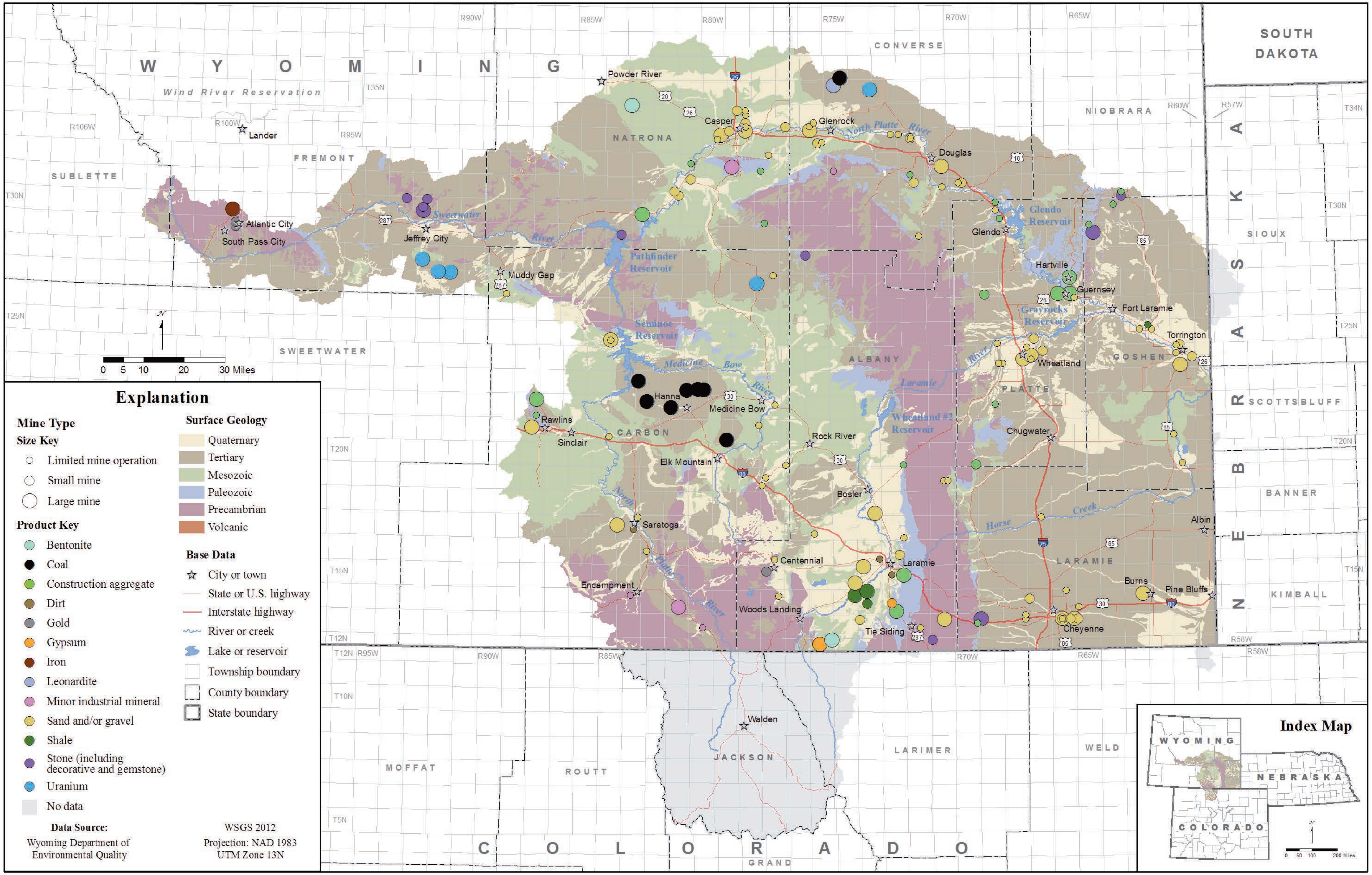

Figure 5-8. Potential groundwater contaminant sources: Wyoming Department of Environmental Quality Land Quality Division permitted mines, {quarries, and pits}, Platte River Basin, Wyoming.

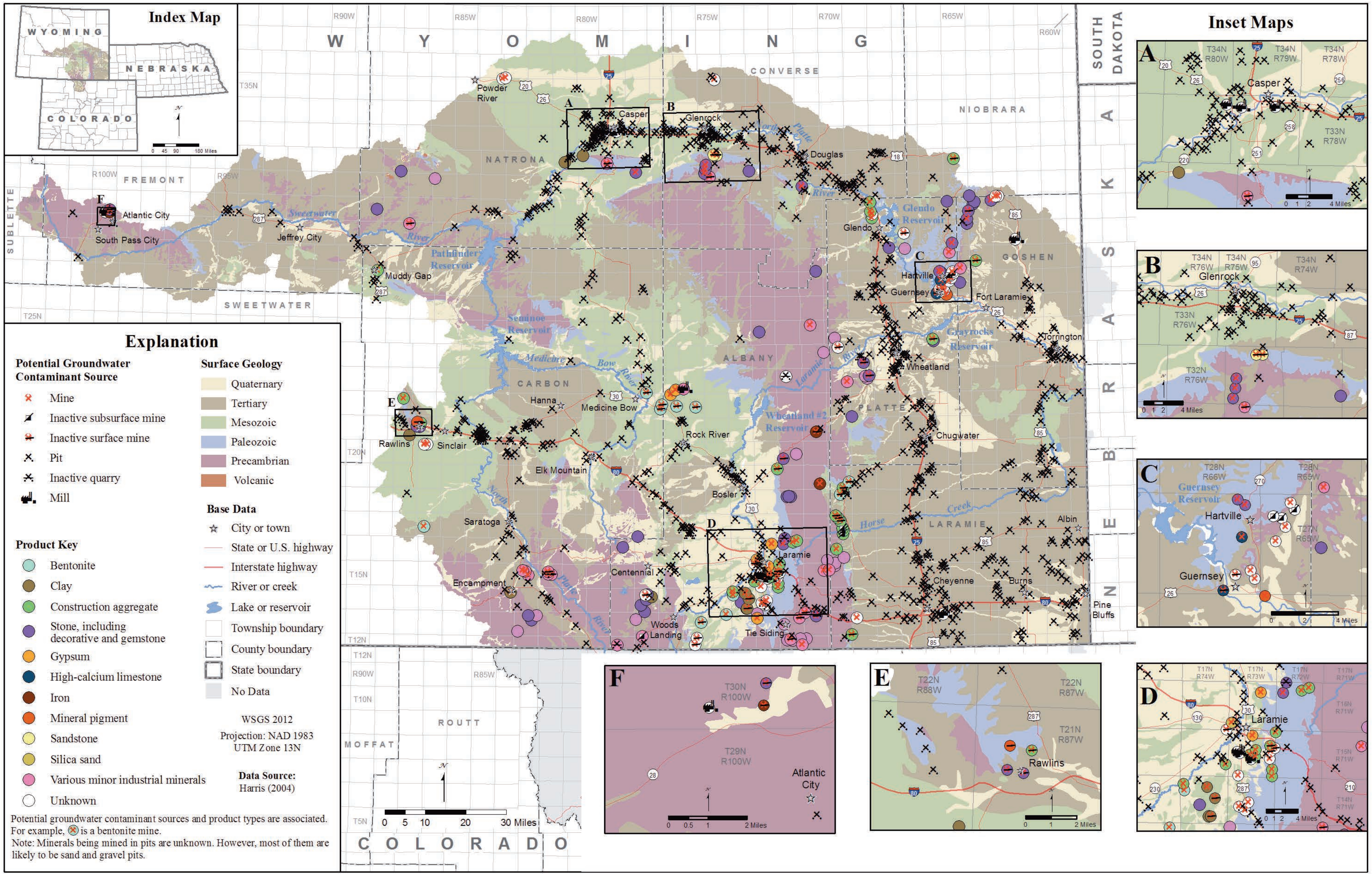

Figure 5-9. Potential groundwater contaminant sources: Wyoming State Geological Survey mapped mines, Platte River Basin, Wyoming, (locations from Harris, 2004).

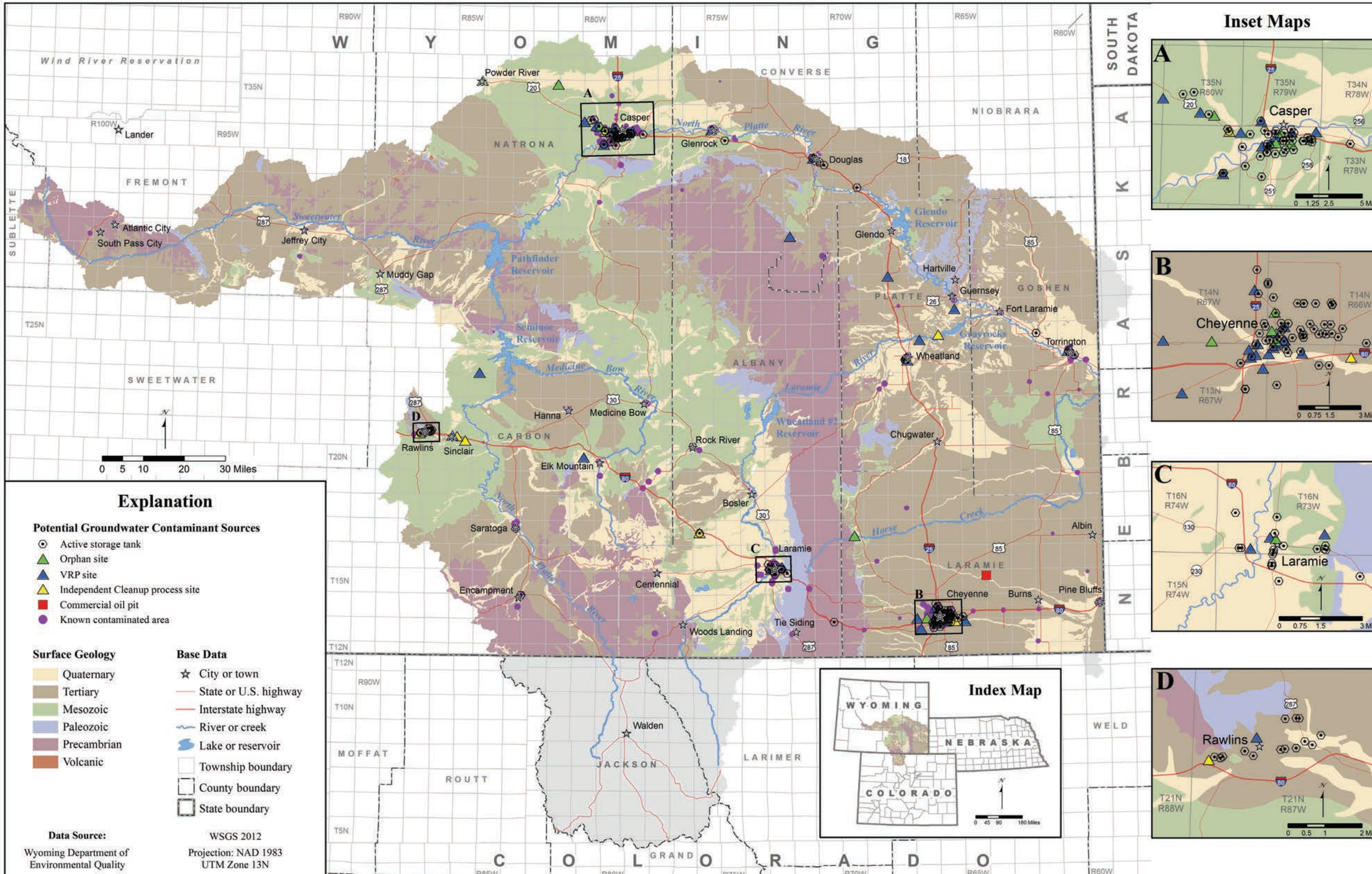

Figure 5-10. Potential groundwater contaminant sources: Wyoming Department of Environmental Quality (WDEQ) permitted storage tanks and commercial disposal pits; WDEQ Voluntary Remediation Program (VRP), Brownfield, Independent cleanup process (ICP), and orphan sites; and known contaminated areas in WDEQ's groundwater program, Platte River Basin, Wyoming.

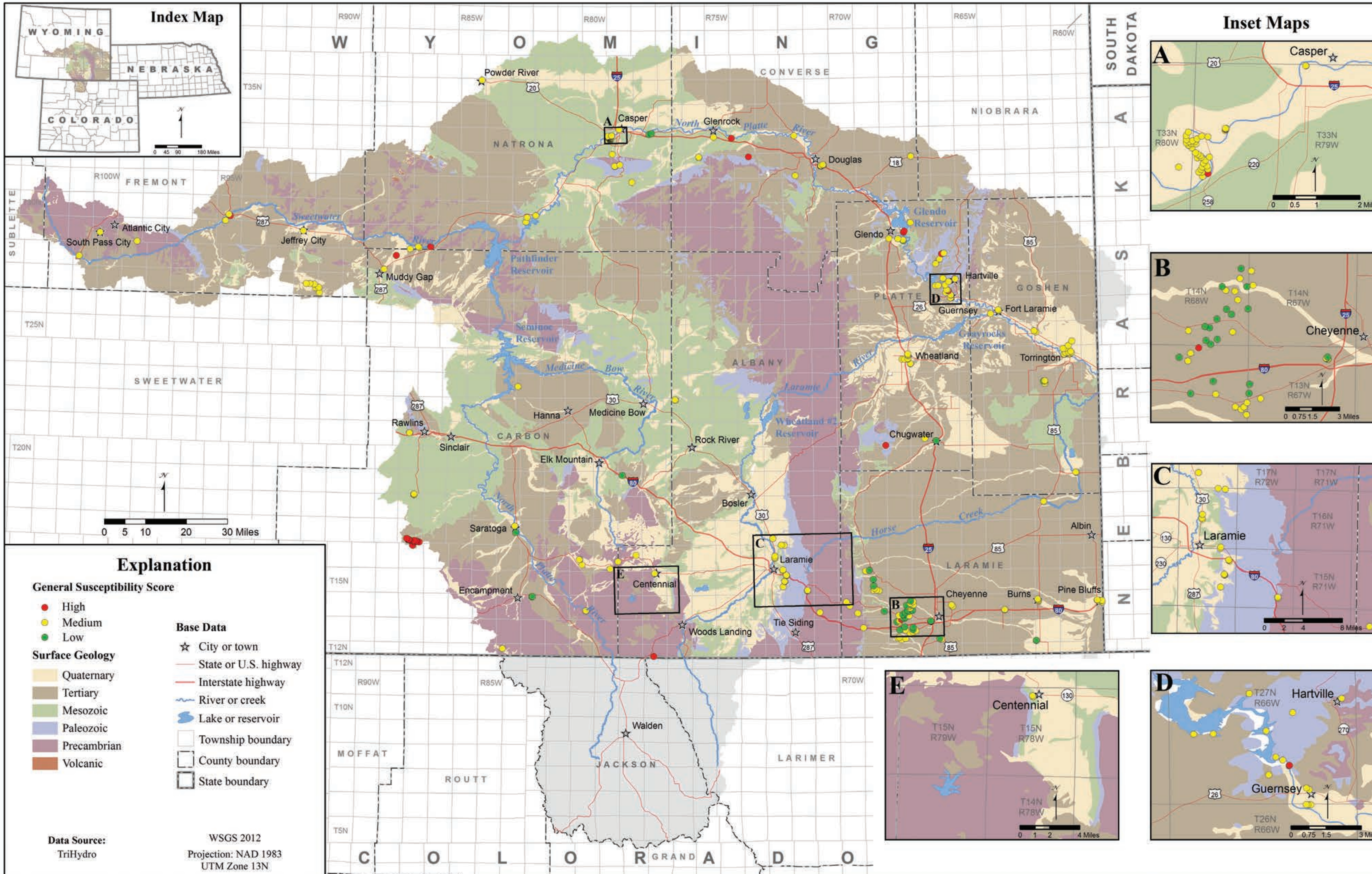

Figure 5-11. Surface Water Assessment and Protection, Platte River Basin, Wyoming.

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, automotive and industrial waste disposal wells, 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 underground injection wells are permitted through the WDEQ Land Quality Division (LQD). Class III wells are used to inject fluids for in situ solution mining of various minerals (e.g., uranium, sulfur, copper, salts, 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 applications. The largest concentration of Class III injection wells in the Platte River Basin is for in-situ uranium recovery located north of Glenrock, Wyoming near the northern margin of the drainage basin.
- **Active and expired WYPDES outfalls:** Discharge of any potential pollutant from a point source into surface waters of the state requires a WDEQ Wyoming Pollutant Discharge Elimination System (WYPDES) permit from the Water Quality Division (WQD). During flow to surface waters where contaminant concentrations may be diluted, discharged waters may infiltrate dry drainages and recharge shallow aquifers, potentially contaminating shallow groundwater resources. Spreader dikes, on-channel reservoirs, ponds, pits and other impoundments are commonly installed along WYPDES flow paths to store 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 Platte River Basin, several of which discharge produced water from oil and gas operations.

Figure 5-6 – Potential groundwater contaminant sources: WDEQ solid and hazardous waste facilities and concentrated animal feeding operations (CAFOs)

- **Solid and hazardous waste facilities -** Permitted by WDEQ Solid and Hazardous Waste Division (SHWD) including:
  - Municipal landfills, and transfer, treatment, and storage facilities.
  - Industrial landfills, treatment, and storage facilities.
  - Solid waste treatment, storage, and disposal facilities.
  - Spill and hazardous waste corrective action sites.
  - Illegal dump sites and historic site cleanups.

Solid and hazardous waste facilities contain a great number of potential contaminants in a variety of configurations. Wastes may be liquid, solid or semisolid forms, stored 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 to groundwater in several ways. 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.

- **CAFOs:** Concentrated animal feeding operations are permitted by the SHWD. Outfalls from CAFOs are also permitted under the WYPDES Program. The primary potential contaminant generated at CAFOs is animal waste. Other farm and ranch potential contaminant sources include stored bulk fuels, antifreeze, used oil, pesticides, and herbicides. Small "ranch dumps," and landfills may also be located near CAFOs.

Figure 5-7 – Potential groundwater contaminant sources: WDEQ storage tanks, commercial wastewater disposal pits, Volunteer Remediation Program (VRP) and Independent Cleanup Process (ICP) sites, brownfield sites, orphan sites, and Groundwater Program Known Contaminated Areas

- **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.
- **VRP and ICP 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). By definition, sites enrolled in this program are associated with contaminated soil or groundwater or both.
- **Orphan and brownfield assistance sites:** These are contaminated sites where a viable responsible party other than the state does not exist (orphan), or sites with known or suspected contamination that are owned by local, state or federal government entities (brownfield).
- **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 for sale. Releases can occur from operational malfunctions, underground leaks directly from pits, and leaks from pipes and storage tanks.
- **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.

Figures 5-8 through **5-10** 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 become hydraulically connected to the water table along with any contaminants. Exposure of metal-rich lithologies to the atmosphere can oxidize and mobilize dissolved concentrations. In addition, any release of bulk products (fuel, antifreeze, lubrication and hydraulic oils, etc.) and wastes stored or generated can more quickly infiltrate to the subsurface within disturbed areas associated with the operations of these facilities.

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 DEQ'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.
- **Active coal mines** mapped by the WSGS are also included in **Figure 5-8**.

Figure 5-9 – 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 5-10 – 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 5-10** was compiled prior to and independently of the data compiled for **Figures 5-8** and **5-9**, it might provide a more comprehensive picture of mining locations in the Platte River Basin.

5.7.3 Discussion

To be included in this study, location data for potential contaminant sources had to be in formats that could be imported into ARC/GIS format. Some of the types of facilities listed below are not found in the Platte River Basin. Some contaminant source types do not currently have the location data in the ARC/GIS format required for mapping, or the data exist but were not available. The following types of potential groundwater contaminant sources were not mapped in this study:

- Although a large number of public owned treatment works (POTWs) and septic systems exist in the Platte 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 **(Figure 5-5)**.
- Areas where pesticides and herbicides are applied were not mapped for this study. The distribution of irrigated lands presented in the Platte River Basin Final Report (Trihydro Corporation and others, 2006a - Figures 2-7 through 2-13) shows the primary areas where agricultural chemicals would generally be applied in the Platte River Basin. In addition, recent USGS reports (Bartos and others, 2009; Eddy-Miller and others, 2013) present the results of sampling to characterize pesticide occurrences in groundwater in areas determined by the earlier SDVC (Hamerlinck and Arneson, 1998) report 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 (UGC) sites in the Platte River Basin.
- Produced water pits regulated by the WOGCC, oil and gas field plants and compressor stations were not individually mapped for this study. These potential sources are located within the oil and gas fields mapped in **Figure 5-4.**
- 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 WDEQ/SHWD but are not shown on **Figure 5-6** 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 Platte River Basin Available Groundwater Determination, Technical Memorandum.

5.7.4 Source Water Assessment Program, Wyoming Water Quality Monitoring Strategy and Associated Groundwater Protection Programs

The federal government, under the Clean Water Act, recognized that states have primary responsibility for implementing programs to 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
- The USGS Pesticide Monitoring Program in Wyoming

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

<u>The Source Water Assessment Program (SWAP)</u>

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. Additional information on the SWAP in Wyoming can be accessed online at:

http://deq.state.wy.us/wqd/www/SWP%20WHP/SWAP%20FAQs.asp.

Copies of Source Water Assessment Reports for specific PWSs in the Platte River Basin can be accessed at: http://deq.state.wy.us/wqd/www/SWP%20WHP/index.asp.

<u>Water Quality Monitoring Strategy</u>

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; USGS, variously dated)
- Phase III – Groundwater monitoring plan implementation and assessment
- Phase IV – Education and outreach for local groundwater protection efforts

<u>Phase I – Aquifer prioritization</u>

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, and present 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
    - Rural residential development
    - Oil and gas exploration, development, and pipelines
    - Known and potential contaminant sources
    - Croplands and urban areas
    - Mining,
    - 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/downloads/NGWA%20Final.pdf. 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 manmade 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://waterdata.usgs.gov/ wy/nwis/qw/.
- 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, U.S. Environmental Protection Agency (EPA), Wyoming Water Development Office, Wyoming State Geological Survey, and Wyoming State Engineer's Office. 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 various 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 data set 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.usgs.gov/sir/2009/5024/; http://pubs.usgs.gov/fs/2009/3006/ and 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 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 address the common goal of 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.