National Water-Quality Assessment

Yellowstone River Basin

Environmental Setting of the Yellowstone River Basin, Montana, North Dakota, and Wyoming

Water-Resources Investigations Report 98-4269

U.S. Department of the Interior
U.S. Geological Survey

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By Ronald B. Zelt, Greg Boughton, Kirk A. Miller, Jon P. Mason, and Laura M. Gianakos

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Prepared as part of the
NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

Cheyenne, Wyoming
1999

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
millimeter (mm)	0.03937	inch
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
square kilometer (km^2)	0.3861	square mile
cubic meter (m^3)	35.31	cubic foot (ft^3)
barrel (bbl), petroleum	42	gallon
barrel (bbl), petroleum	0.159	cubic meter (m^3)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
kilogram (kg)	2.205	pound (lb)
megagram (Mg)	1.102	short ton (2,000 lb)

Temperature can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by using the following equations:

$$°C = 5/9\ (°F - 32)$$
$$°F = 9/5\ (°C) + 32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

Natural and anthropogenic factors influence water-quality conditions in the Yellowstone River Basin. Physiography parallels the structural geologic setting that is generally composed of several uplifts and structural basins. Contrasts in climate and vegetation reflect topographic controls and the midcontinental location of the study unit. Surface-water hydrology reflects water surpluses in mountainous areas that are dominated by snowmelt runoff, and arid to semiarid conditions in the plains that are dissected by typically irrigated valleys in the remainder of the study unit. Principal shallow aquifers are Tertiary sandstones and unconsolidated Quaternary deposits.

Human population, though sparsely distributed in general, is growing most rapidly in a few urban centers and resort areas, mostly in the northwestern part of the basin. Land use is areally dominated by grazing in the basins and plains and economically dominated by mineral-extraction activities. Forests are the dominant land cover in mountainous areas. Cropland is a major land use in principal stream valleys. Water use is dominated by irrigated agriculture overall, but mining and public-supply facilities are major users of ground water. Coal and hydrocarbon production and reserves distinguish the Yellowstone River Basin as a principal energy-minerals resources region. Current metallic ore production or reserves are nationally significant for platinum-group elements and chromium.

The study unit was subdivided as an initial environmental stratification for use in designing the National Water-Quality Assessment Program investigation that began in 1997. Ecoregions, geologic groups, mineral-resource areas, and general land-cover and land-use categories were used in combination to define 18 environmental settings in the Yellowstone River Basin. It is expected that these different settings will be reflected in differing water-quality or aquatic-ecological characteristics.

INTRODUCTION

Beginning in 1991, the U.S. Congress appropriated funds for the U.S. Geological Survey (USGS) to commence full-scale implementation of the National Water-Quality Assessment (NAWQA) Program. Goals of the program include the identification, description, and explanation of major natural and anthropogenic factors that influence water-quality conditions (Gilliom and others, 1995). Important components of the NAWQA Program are investigations of more than 50 major river basins and aquifers, called study units. Water-quality conditions measured at sites in these study units may be misinterpreted unless spatial patterns and environmental characteristics of associated drainages or flow-path areas are understood.

The Yellowstone River Basin (YRB) was among the set of 13 NAWQA study-unit investigations begun in 1997. The YRB study unit (fig. 1) consists of the entire 182,000 km^2 area drained by the Yellowstone River and its tributaries, including the Wind/Bighorn, Powder, Tongue, and Clarks Fork Yellowstone Rivers. The Yellowstone River is the largest tributary of the Missouri River (Missouri Basin Inter-Agency Committee, 1969), and the mean annual discharge (361 m^3/s) of the Yellowstone at its confluence with the Missouri in western North Dakota represents about 55 percent of their combined discharge (Shields and others, 1997).

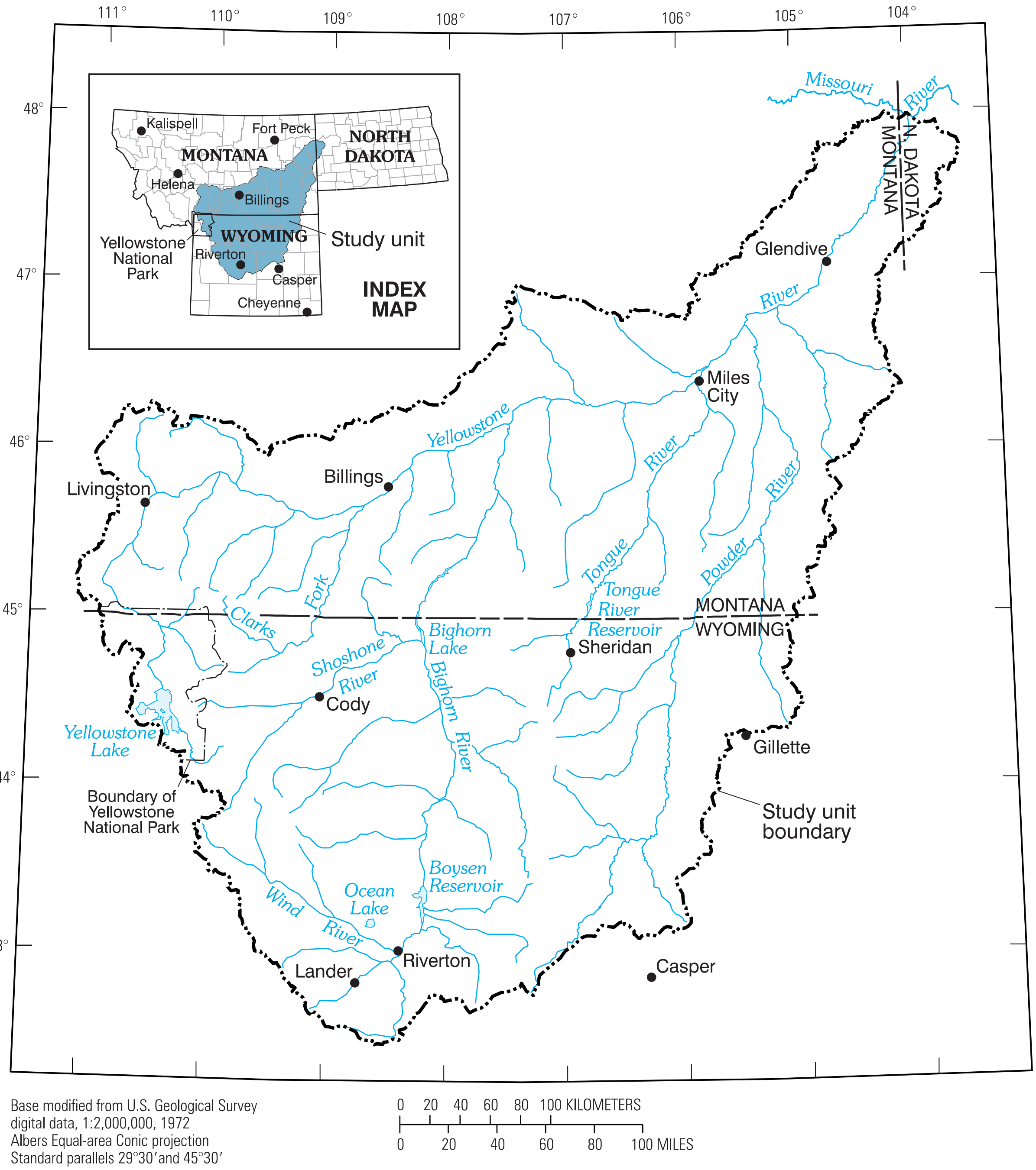


Figure 1. Location of the Yellowstone River Basin study unit, and selected cities, Montana, North Dakota, and Wyoming.

The purpose of the study-unit investigation is to increase the scientific understanding of surface- and ground-water quality and the factors that influence water quality in the YRB. Important water-quality issues in the YRB generally are related to effects of land and water management practices, but some are related to natural factors. For example, sedimentation problems in streams and reservoirs in parts of the YRB are likely a result of naturally erodible soils and natural processes such as post-wildfire landslides and debris flows, as well as human land-use activities that remove vegetation, disturb soils, and steepen or overload slopes. Other major water-quality issues include trace elements, toxic compounds, and salinity (Miller and Quinn, 1997).

Purpose and Scope

This report describes the environmental settings of the YRB, including natural and anthropogenic factors believed to influence water-quality conditions. Specifically, the report provides historical and baseline information for the topical studies to be undertaken as part of the NAWQA study-unit investigation of the YRB. An initial stratification (subdivision into areas having greater homogeneity than the whole YRB) of the study unit based on its environmental settings also is presented.

Previous Studies

Early explorers of the YRB include Larocque in 1805, Clark in 1806, Colter in 1807-08, Drouillard in 1808, Henry in 1809, Hunt in 1811, Wyeth in 1833, and Raynolds and Maynadier in 1859-60 (U.S. Department of the Interior, 1965; Missouri Basin Inter-Agency Committee, 1969). The U.S. Army sent exploratory expeditions into the YRB, beginning with the 1856 expedition led by Lt. G.K. Warren, accompanied by geologist F.V. Hayden. Hayden mapped the general geology of the Wind River Basin in 1859-60 and the Yellowstone-Teton area in 1868. The Washburn-Doane expedition of 1870 ascended the Yellowstone River and received official credit for the “discovery” of what became Yellowstone National Park. Also in 1870, the Yale Scientific Expedition, led by O.C. Marsh, explored the Bighorn Basin. The U.S. Geological and Geographical Survey of the Territories began in 1871, under the direction of Hayden, and produced impressive documentation of the geologic and scenic wonders of the Yellowstone Plateau, due in large part to the photography by W.H. Jackson and paintings by Thomas Moran.

Settlement and development of the YRB followed the period of exploration. Numerous studies have been conducted in local areas and of individual resources or environmental factors within this vast area. Selected previous studies that were broad in geographic extent and that examined multiple geographic or environmental factors are the topic of the remainder of this section.

A general reconnaissance of the northern Great Plains was made by the USGS in 1924 to classify the public domain into three principal land-suitability categories: land that would be best suited to production under irrigation, by dry-farming methods, or as grazing land (Aldous and Deeds, 1929). That study included part of the YRB east of the Rocky Mountains and north of 43^{o}N latitude, and described the physiography, soils, and vegetation.

The U.S. Department of the Interior’s Missouri River Project was a basin development program active from 1945-65 that produced separate studies of seven subbasins that together compose the YRB (for examples, the reader is referred to U.S. Department of the Interior, 1949; 1965). The purpose of these studies was to promote the use and management of the public lands in the best interests of the public, consistent with proper conservation practices (U.S. Department of the Interior, 1965). A recommendation resulting from that program was the sale of a large part of the vacant, unreserved public domain that would contribute more to the local economy in private ownership (U.S. Department of the Interior, 1965).

During 1964-69, a comprehensive study of the Missouri River Basin was conducted to guide long-range planning for multipurpose development of water and related land resources during 1970-2020 (Missouri Basin Inter-Agency Committee, 1969). The recommendations made in the final report included the following: (1) construction of 78 reservoirs to provide 2.6 million m^3 of additional storage; (2) development of 2,500 km^2 of land for irrigation; (3) protecting 179 km of stream banks against erosion; (4) designating 507 km of scenic rivers; and (5) acquisition of 186 km^2 of land for wildlife management (Missouri Basin Inter-Agency Committee, 1969). The planners foresaw conflicts between environmental values related to scenic beauty and preservation of wild streams and economic-development values related to an extensive system of reservoirs and irrigation projects. Given the surface-water emphasis of the interagency study, a subsequent study (Taylor, 1978) of the Missouri River Basin was done to describe its ground-water resources and indicate areas where information was lacking.

During the late 1960s and through the 1970s, a series of water-resources assessments were conducted in several moderately large study areas included in the YRB (for examples, the reader is referred to Miller, 1979; 1981; Taylor, 1968). The Yellowstone Impact Study, begun in 1974 by the Montana Department of Natural Resources and Conservation, evaluated potential physical, biological, and water use impacts of water development on the middle and lower sections of the Yellowstone River Basin in Montana (Newell, 1977). Due to the importance of ground water for domestic and stock consumption, studies of several areas of the Powder River Basin emphasized the major aquifers in those areas. Several ground-water studies from this period examined the potential hydrologic effects of the anticipated development of coal resources in the Powder River Basin (Slagle and others, 1985; Van Voast and others, 1978; Van Voast and Thompson, 1982). A notable large-area study examining a broader scope of effects of coal development was the Northern Great Plains Resource Program (1974)

Following enactment of the Surface Mining Control and Reclamation Act of 1977 (PL 95-87), requiring the assessment of hydrologic impacts prior to issuance of mining permits, a series of reports summarizing the hydrology of coal provinces were prepared by the USGS. The drainages of the Clarks Fork Yellowstone River, Pryor Creek, and smaller tributaries to the Yellowstone River in its westernmost Great Plains reach were characterized by Slagle and others (1986). Peterson and others (1987) described the resources of much of the area drained by the Bighorn-Wind and Shoshone Rivers upstream of Bighorn Lake. Slagle and others (1983) characterized the drainages of the Tongue River, Rosebud Creek, and smaller tributaries to the middle reach of the Yellowstone River. Lowry and others (1986) described the hydrology and setting of the Powder River Basin. Drainages of the lower reach of the Yellowstone River were characterized by Slagle and others (1984).

About the northeastern half of the YRB was included in the study area of the USGS' Northern Great Plains Regional Aquifer-System Analysis (RASA) that began in 1981. The objectives of that study were to describe the regional trends of ground-water chemistry, to determine the mechanisms controlling the water chemistry, and to identify flow directions and areas of recharge (Busby and others, 1995). The study focused on Lower Cretaceous through Paleozoic aquifers.

During 1986-90, the USGS conducted studies of the water-quality of the Powder River. The objectives were to (1) determine temporal trends in selected water properties and chemical constituents (Cary, 1989; 1991), and (2) develop a water-quality model of the river to evaluate water-management alternatives (Lindner-Lunsford and others, 1992). Also during the late 1980s, an atlas of the water resources and water hazards of Wyoming was compiled (Ostresh and others, 1990).

ENVIRONMENTAL SETTING

The physical, chemical, hydrological, and ecological characteristics of an area are considered to compose its environmental setting (Stark and others, 1996). In a study unit as large and diverse as the YRB, strong contrasts among these characteristics exist. The water-quality characteristics of the study unit are expected to similarly be diverse and to reflect the environmental contrasts among the areas of water sources and those areas through which the water moves before exiting the YRB. This description of the environmental setting is not exhaustive, but concentrates on the factors believed to influence water quality and aquatic ecology in this study unit.

Both natural and anthropogenic factors affecting water quality are described. Natural factors discussed in this report are those which generally control water-quality characteristics in the absence of human activity. Although water and land use practices sometimes overshadow natural factors, understanding the natural diversity of the YRB is believed to be important in understanding its water-quality conditions. Natural factors include physiography, climate, geology, vegetation, and hydrology. Anthropogenic factors, including population, land cover and land use, water use, and waste disposal, are described following the natural factors.

Physiography

Physiography refers to the physical morphology of the earth's surface. The study unit lies in parts of the Great Plains, Middle Rocky Mountains, Wyoming Basin, and Northern Rocky Mountains physiographic provinces (fig. 2) (Fenneman and Johnson, 1946). A digital map (G.P. Thelin, U.S. Geological Survey, unpub. data, 1992) of Fenneman's physical divisions at a nominal scale of 1:7,500,000 was used to summarize the distribution of physiographic provinces in the YRB. Digital elevation models (U.S. Geological Survey, 1987) for all 1- by 1-degree quadrangles of latitude and longitude in the study unit were assembled and used to summarize elevation. Elevation ranges from 564 m above sea level at the mouth of the Yellowstone River to about 4,200 m on the crest of the Wind River Range.

Fifty-five percent of the study unit lies in the Great Plains Province (fig. 2). The Great Plains feature gently rolling topography in general, but some areas of sharply dissected badlands have developed in easily erodible shales. Most of this area is part of the unglaciated Missouri Plateau section of the Great Plains, but the extreme northeastern end of the YRB lies within the area subjected to continental glaciation. The unglaciated Missouri Plateau section displays the greatest variety of landforms in the Great Plains (Trimble, 1980). The topography of the unglaciated plains largely reflects fluvial dissection of the ancient outwash plain that extended eastward from the Rocky Mountains (Trimble, 1980). The sediments of this surface slope to the east at an average gradient of about 1.9 m/km (Howard and Williams, 1972). In places, the plateau is surmounted by higher erosional remnants of an older depositional surface (Trimble, 1980). Most rivers of this section flow in broad alluvial valleys established prior to the advance of continental ice sheets (Trimble, 1980). Elevations in the Great Plains Province range from 570 to 2,200 m within the study unit, averaging 1,070 m. Local relief typically is less than 150 m, but in parts of the Powder River Basin increases to about 300 m.

The Middle Rocky Mountains Province (fig. 2) contains 35 percent of the study unit and features landforms varying from mountain ranges and high plateaus to intermontane basins, such as the Bighorn Basin. Elevations in this province range from 1,040 to about 4,200 m within the study unit, averaging 2,090 m. Centered in this part of the study unit is the Bighorn Basin, bordered on the west by the Absaroka Range and Beartooth Mountains, on the south by the Owl Creek Mountains, and on the east and northeast by the Bighorn and Pryor Mountains. To the north, the basin is topographically open where it merges into the Crazy Mountains Basin (or Syncline) of south-central Montana (Lageson and Spearing, 1988), not shown in figure 5.

Most of the mountain ranges have a high axial crest surmounting a broad, high-elevation erosional surface that slopes gently outward until dropping off abruptly to the lowlands. Remnants of this surface are found on gravel-capped mesas in the adjacent basins. Lower erosional levels are evidenced by lower mesas and by broad, paired alluvial terraces (Howard and Williams, 1972, p. 29).

Badlands topography has developed in parts of the Bighorn Basin where the Willwood Formation of Tertiary age crops out (Mears and Marston, 1990). Local relief is 150 to 300 m in this basin, which is topographically classified as plains with high hills (Mears and Marston, 1990).

The Bighorn and Wind River mountain ranges are broad anticlines flanked by hogbacks. The Beartooth Mountains are high plateaus atop several uplifted blocks that are dissected by numerous glaciated river valleys (Page and Zientek, 1985). The Absaroka Range consists of thick volcanic deposits presenting a rugged topography dominated by deep, steep-sided valleys with erodible slopes and large areas of cliffs and talus (Despain, 1990). All of these mountain ranges feature local relief typically in excess of 1,000 m.

The volcanic Yellowstone Plateau lies west of the Absaroka Range and features an undulating, almost level surface averaging about 2,500 m in elevation. Both the Yellowstone Plateau and the Absarokas are topographically classified as tablelands with high relief, being 50 to 80 percent gently sloping terrain, with 50 to 75 percent of that occurring in uplands (Mears and Marston, 1990).

A few broad valleys with large meandering rivers are located within the Middle Rockies, but stream gradients within the mountainous areas generally are steep. Dense vegetation and armored streambeds resist erosion, but where soft rocks are exposed or vegetation is disturbed, rapid erosion occurs (Missouri Basin Inter-Agency Committee, 1969). The drainage network of the Middle Rocky Mountains Province features several deep canyons, such as the Bighorn and

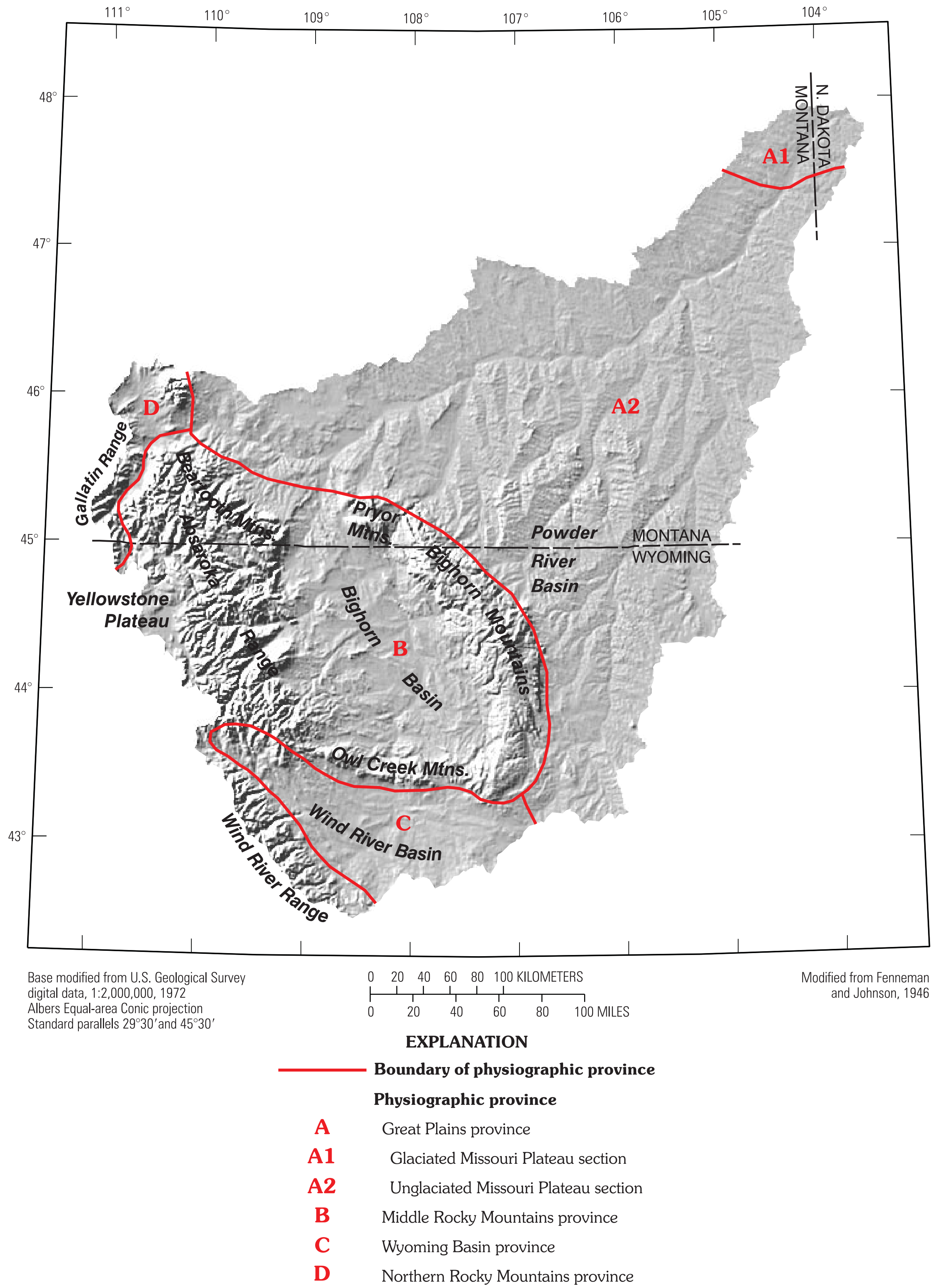


Figure 2. Location of physiographic provinces, Yellowstone River Basin, Montana, North Dakota, and Wyoming.

Wind River Canyons, where rivers cut through mountain ranges rather than following lowland courses around the barriers. These canyons are attributed to superimposition of stream courses from the surface of sediments that formerly filled the basins to higher levels than at present (Howard and Williams, 1972).

The part of the Wyoming Basin physiographic province contained within the study unit, composing about 7 percent of the study unit, corresponds to the Wind River Basin. The boundary between this province and the Great Plains is the subtle surface expression of the Casper Arch (fig. 5); this gap south of the Bighorn Range is the only area where the mountainous western border of the Great Plains is interrupted. The Wind River Basin is bounded on the north by the Owl Creek Mountains, on the west by the Wind River Range (fig. 2), and on the south by minor ranges associated with the Sweetwater uplift (fig. 5). Terrace and pediment surfaces form extensive tablelands, and locally prominent badlands are eroded into soft Tertiary sediments (Keefer, 1965). Elevation in this province ranges from 1,440 to 3,600 m within the study unit, averaging about 1,840 m. Local relief is typically 150 to 300 m.

The Northern Rocky Mountains Province (fig. 2) contains about 3 percent of the study unit. This province is separated from the Middle Rocky Mountains Province only by the Yellowstone River valley and Yellowstone Plateau. Elevation in this province ranges from 1,310 to 3,350 m within the study unit, averaging about 1,930 m.

A hypsometric curve for the YRB illustrates (fig. 3) that only 2.3 percent of the study unit lies more than 3,100 m above sea level, which roughly corresponds to the alpine zone above timberline (compare, Despain, 1990; Thilenius and Smith, 1985). Also, about 82 percent of the study unit is less than 2,100 m in elevation and, thus lies below the densely forested mountain zone, discussed elsewhere in this report.

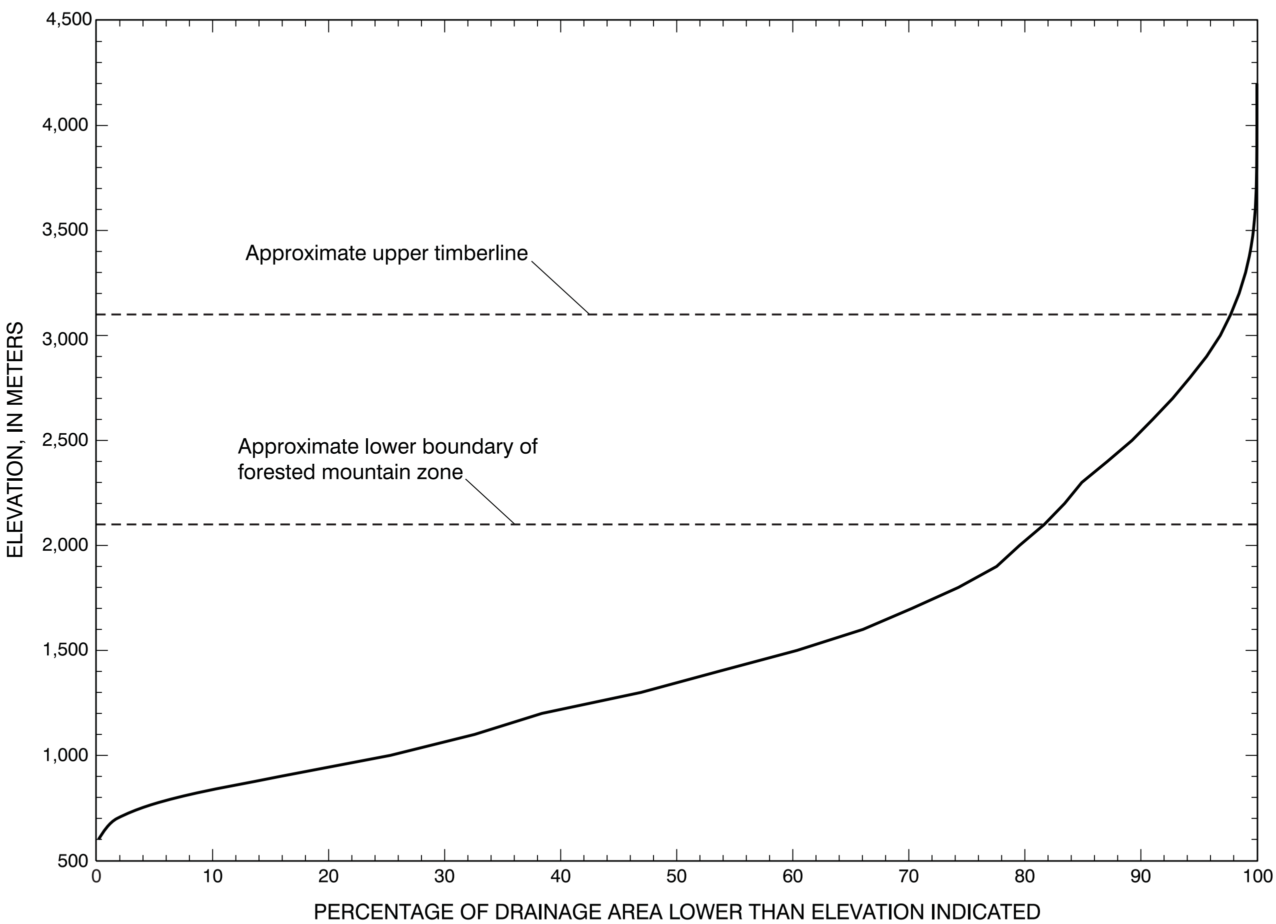


Figure 3. Hypsometric curve for Yellowstone River Basin.

Climate

Climate in the study unit ranges from cold and moist in the mountainous areas to temperate and semiarid in the plains areas. Primarily because of its midcontinental location, the basin's weather is characterized by fluctuations and extremes (Missouri Basin Inter-Agency Committee, 1969). The interaction between air masses originating in the Gulf of Mexico, the northern Pacific Ocean, and the Arctic regions is largely responsible for the seasonal climate regimens found within the study area. The Gulf air tends to dominate in spring and early summer, but Arctic air dominates in winter (Missouri Basin Inter-Agency Committee, 1969).

Mean annual temperatures range from less than 0^{o}C at Yellowstone Lake to about 10^{o}C along the Bighorn River valley in Montana (National Climatic Data Center, digital data, 1994). Annual temperature extremes range from about -40^{o}C during the winter to hotter than 38^{o}C during the summer (Western Regional Climate Center, digital data, 1997). Temperatures generally are coldest in January, when average daily lows range from less than -18^{o}C in higher elevations to about -8^{o}C near Livingston, Mont. (fig. 4) (Western Regional Climate Center, digital data, 1997), and average monthly temperature ranges from less than -13^{o}C in Yellowstone National Park to about -3^{o}C near Livingston, Mont. (National Climatic Data Center, digital data, 1994). July normally is the warmest month, with average daily highs ranging from about 22^{o}C in higher elevations to about 32^{o}C in some valleys of the Great Plains and Wyoming Basin Provinces (Western Regional Climate Center, digital data, 1997). Average July temperature ranges from about 12^{o}C in higher elevations to about 24^{o}C in some valley locations (National Climatic Data Center, digital data, 1994). The average frost-free period ranges from less than 10 days at high elevations (Marston and Anderson, 1991) to more than 140 days on the plains and in lower basins (U.S. Department of the Interior, 1965). The climate is cold enough at some sites to form permanent ice (permafrost) in the ground: local permafrost occurs at elevations as low as 2,400 to 2,600 m on north slopes near Yellowstone National Park (Pierce, 1979).

In the YRB, 40 to 45 percent of the annual precipitation falls during April through June at most locations (fig. 4), but this seasonality diminishes in mountainous areas. Mean annual precipitation ranges from about 150 mm (5.9 in.) in the central parts of the Bighorn and Wind River Basins to more than 1,500 mm (59 in.) at high elevations in the mountains near Yellowstone National Park (Oregon Climate Service, 1995a, 1995b). Snowfall composes a substantial part of annual precipitation in most years, with average annual snowfall ranging from less than 300 mm (12 in.) in parts of the Bighorn Basin to more than 5,200 mm (200 in.) near Yellowstone National Park (Western Regional Climate Center, digital data, 1997). The mountain ranges in the study unit cause precipitation to vary strongly with elevation, because in mountainous terrain, most of the spatial variation in precipitation is explained by orographic effects of the large-scale terrain features (Daly and others, 1994). Annual precipitation in the plains areas generally is more variable from year to year, and less than in the mountains (Slagle and others, 1983).

Evaporation varies with temperature, which, in turn, is strongly affected by elevation (Reider, 1990). Evaporation in the YRB is affected more by prevailing wind and sky conditions than by latitude, as shown by published maps of mean annual evaporation for 1956-70 (Farnsworth and others, 1982). Evaporation is greatest in the windswept basins and prairies where the mean annual total generally exceeds 900 mm (35 in.), and surpasses 1,100 mm (43 in.) in parts of the Bighorn and Powder River Basins and Yellowstone River valley. In the cool, often cloud-shrouded highlands of the Absaroka and Beartooth Mountains, mean annual evaporation is less than 500 mm (Martner, 1986). Evaporation and precipitation together distinguish the moist, mountain forest ecosystem from the lower-elevation regions where evaporation exceeds precipitation (Ostresh and others, 1990; Marston and Anderson, 1991).

Geology

Structure

The YRB contains parts of three geologic provinces: the uplifts and basins of the Rocky Mountain foreland, the Yellowstone Plateau, and the Absaroka volcanic field (Snoke, 1993). The structural framework of uplifts and sedimentary basins is shown in figure 5. This section of the report presents a brief overview of the principal structural features of the study unit.

Volcanic Fields and Uplifts

The Absaroka volcanic field and the Yellowstone Plateau are the two major post-Laramide (Late Cretaceous through Paleocene) volcanic fields in the YRB.

The Beartooth, Bighorn, Owl Creek, and Wind River Mountain ranges are the major uplifted areas. The basement-cored uplifts commonly feature complex structures, including foliation, small-scale folds, shear zones, and igneous dikes (Brown, 1993).

The Absaroka volcanic field of Tertiary age is the largest, least-studied volcanic province in the conterminous western United States (Snoke, 1993). This massive volcanic field covers about 23,000 km^2 to a maximum thickness of about 1,500 m (Smedes and Prostka, 1972), and extends well beyond the Absaroka Range itself, so that some workers name it the Absaroka-Gallatin volcanic province (Chadwick, 1970). The volcanic rocks are mostly composed of andesite and dacite; units are chiefly flows, breccias, and stocks. Eruptive centers are aligned along two subparallel northwest-trending structural zones (Chadwick, 1970), one of which includes the Emigrant-Mill Creek, Independence, New World, and Sunlight mineral districts (fig. 9) (Elliott and others, 1983; 1993). An overall pattern of progressively younger eruptive centers transgressing from northwest to southeast has been suggested (Snoke, 1993). The vent areas for the volcanics were predominantly calc-alkaline stratovolcanoes and shield volcanoes composed of lava flows, flow breccias, mudflows, avalanche debris, and tuff in a chaotic assemblage called vent facies (Smedes and Prostka, 1972). Outward from the volcanic centers, the vent facies rocks interfinger with, and grade into, reworked volcanic sedimentary rocks--mainly volcanic conglomerate, breccia, volcanic sandstone and siltstone, and airfall tuff that together are called alluvial facies (Smedes and Prostka, 1972). The volcanic field may have originally covered much of the Bighorn Basin (Love, 1939; Smedes and Prostka, 1972), and extends into the south-central part of the Beartooth uplift (Montagne, 1982, p. 12). However, there is no evidence to indicate what was the northernmost extent of this volcanic field (Smedes and Prostka, 1972).

The Yellowstone Plateau is the product of volcanic eruptions of Quaternary age. Each of three cycles of volcanic activity climaxed with an explosive eruption that produced a voluminous rhyolitic ash flow and a large collapse caldera (Christiansen and Blank, 1972). Rhyolites predominate among the volcanic rocks of the plateau, but basalts also occur. The enormous caldera, 70 by 45 km across and formed in the third volcanic cycle, has been partly filled by rhyolitic lava flows, and is surrounded by a ring of predominantly rhyolitic welded tuff (Christiansen and Blank, 1972). The ash flows cover several hundred km^2, and eolian ash deposits are widespread throughout the western U.S. (Snoke, 1993). With the volume of expelled Quaternary volcanic material totalling about 8,000 km^3, Yellowstone may be the world's largest center of active silicic volcanism (Smith and Braile, 1993). At the present time, the extremely high flow of heat from the Yellowstone Plateau (Smith and Braile, 1993) is evidence that magmas, partial melts, and extensive hydrothermal systems lie beneath the caldera.

A third volcanic area, the Sliderock Mountain (fig. 5) area, lies north of the Beartooth uplift and is underlain by mainly intrusive, volcanic, and volcaniclastic rocks that correlate with deposits of the Livingston Group that lie to the north and northwest (Elliott and others, 1993). The Livingston Group is a thick sequence of volcanic sedimentary rocks that was derived principally from a volcanic field to the northwest (Roberts, 1963) that lies well outside the YRB. However, within the Sliderock Mountain area the geology is dominated by the remains of a deeply eroded Upper Cretaceous stratovolcano composed of lahar deposits and andesite lava flows (Elliott and others, 1993).

The Beartooth uplift, a broad fault-bounded Laramide uplift, includes all of the Beartooth Mountains and merges with the northern Absaroka Range along the south-central part of the uplift (Elliott and others, 1993). The Beartooth uplift is bounded on the east by the Bighorn Basin, on the west by the alluvium-filled valley of the Yellowstone River, and on the south by the Clarks Fork Yellowstone River (Elliott and others, 1983). The Beartooth uplift contains a core of Precambrian crystalline rocks—gneiss, granitics, and supracrustal rocks (Page and Zientek, 1985)—flanked by Paleozoic and younger rocks, and is bounded by thrust faults (Casella and others, 1982). An upper plate of metasedimentary and plutonic rocks was displaced about 15 km toward the north-northeast along a low-angle thrust fault dipping approximately 30^{o} to the southwest (Brown, 1993; Page and Zientek, 1985). Along the southwest marginal thrust fault, Precambrian rocks crop out from beneath the Absaroka volcanic field and Paleozoic sedimentary rocks; the western section of the uplift features metasedimentary rocks intruded by granitics; and the eastern two-thirds of the uplift contains mainly gneisses (Casella and others, 1982; Mueller and others, 1985).

Along the northern edge of the Beartooth Mountains, the Stillwater Complex (fig. 5) of Precambrian age, a mafic to ultramafic, layered igneous intrusion

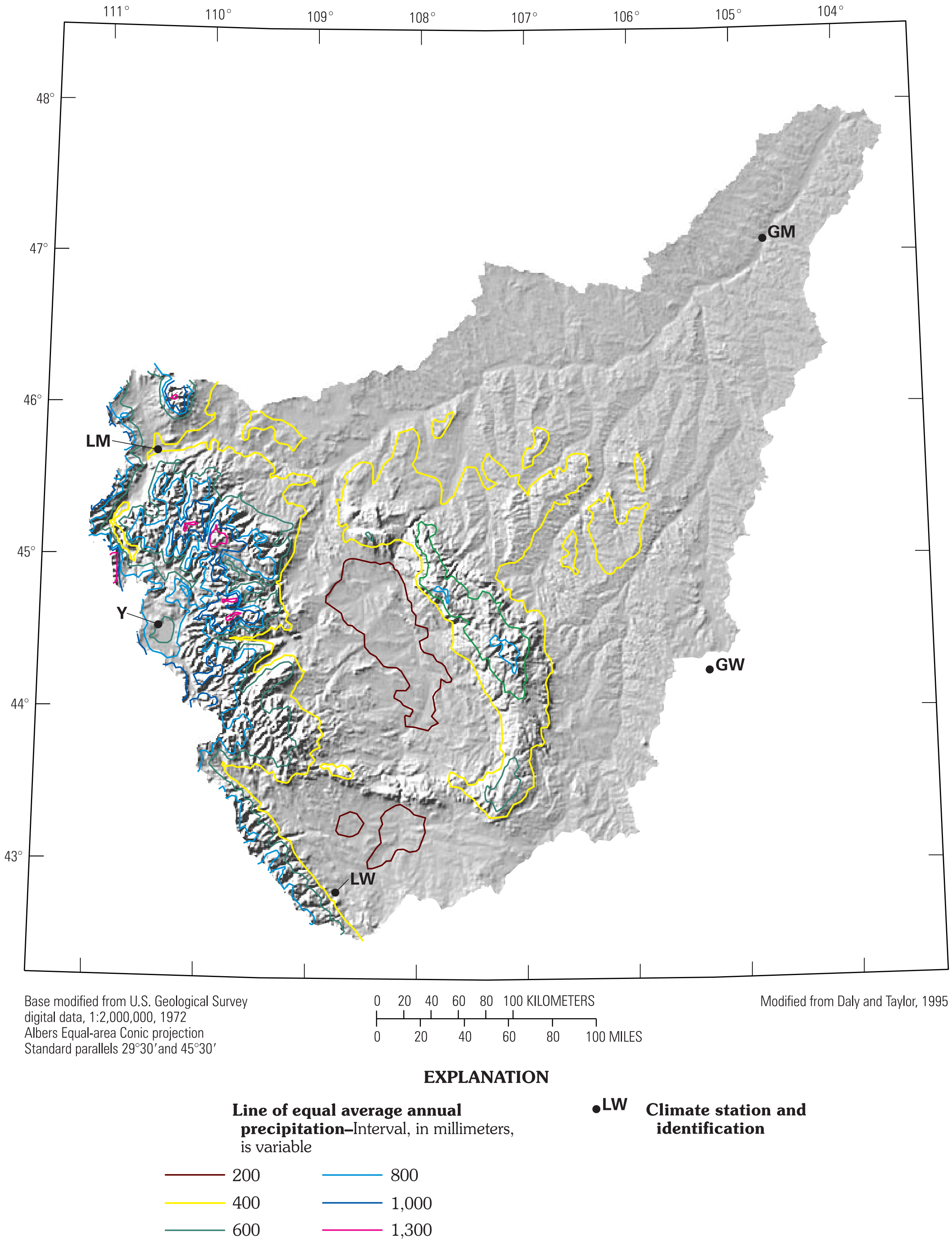


Figure 4. Average annual precipitation, Yellowstone River Basin, Montana, North Dakota, and Wyoming, and graphs showing mean daily precipitation and temperature at selected stations.

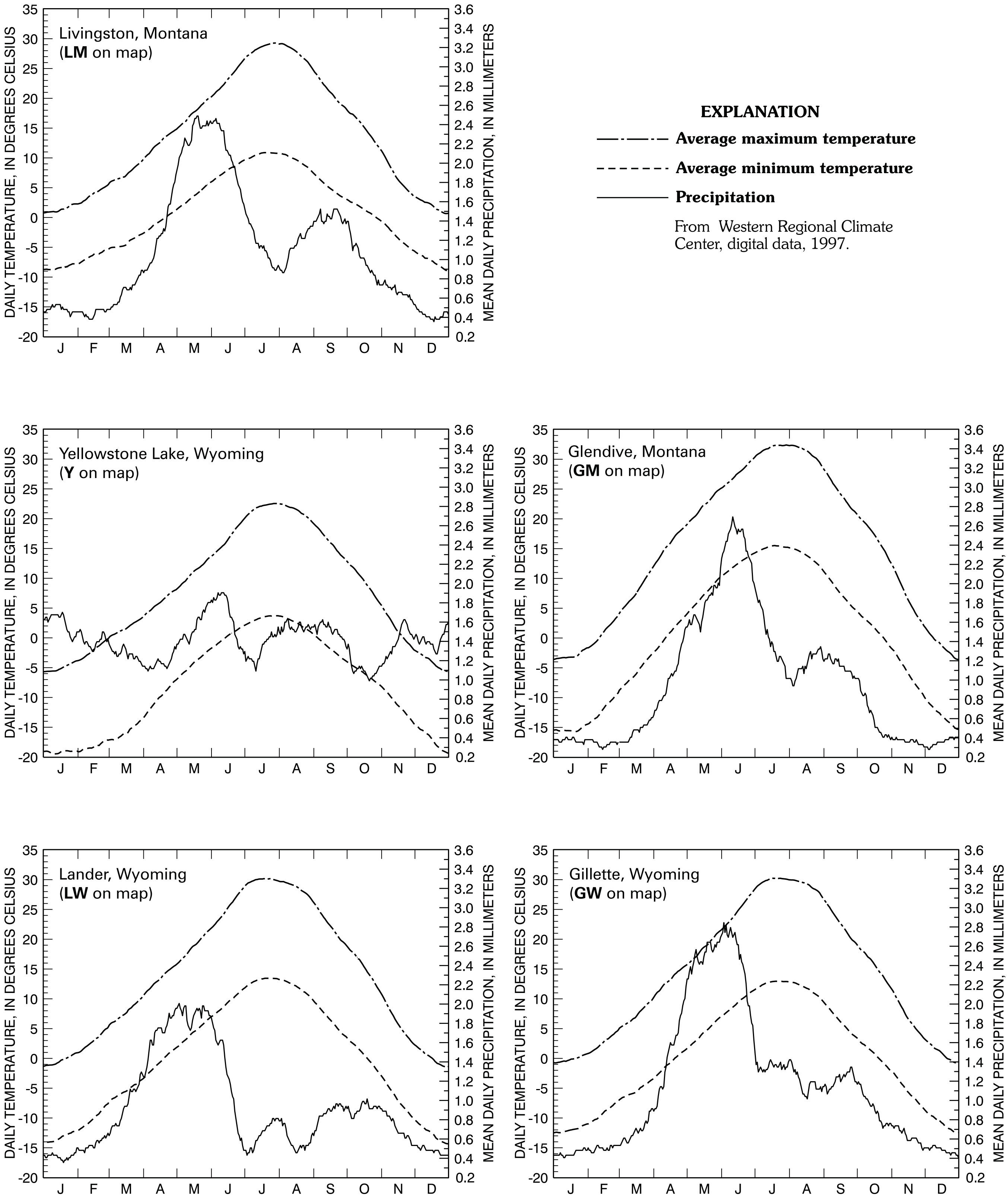
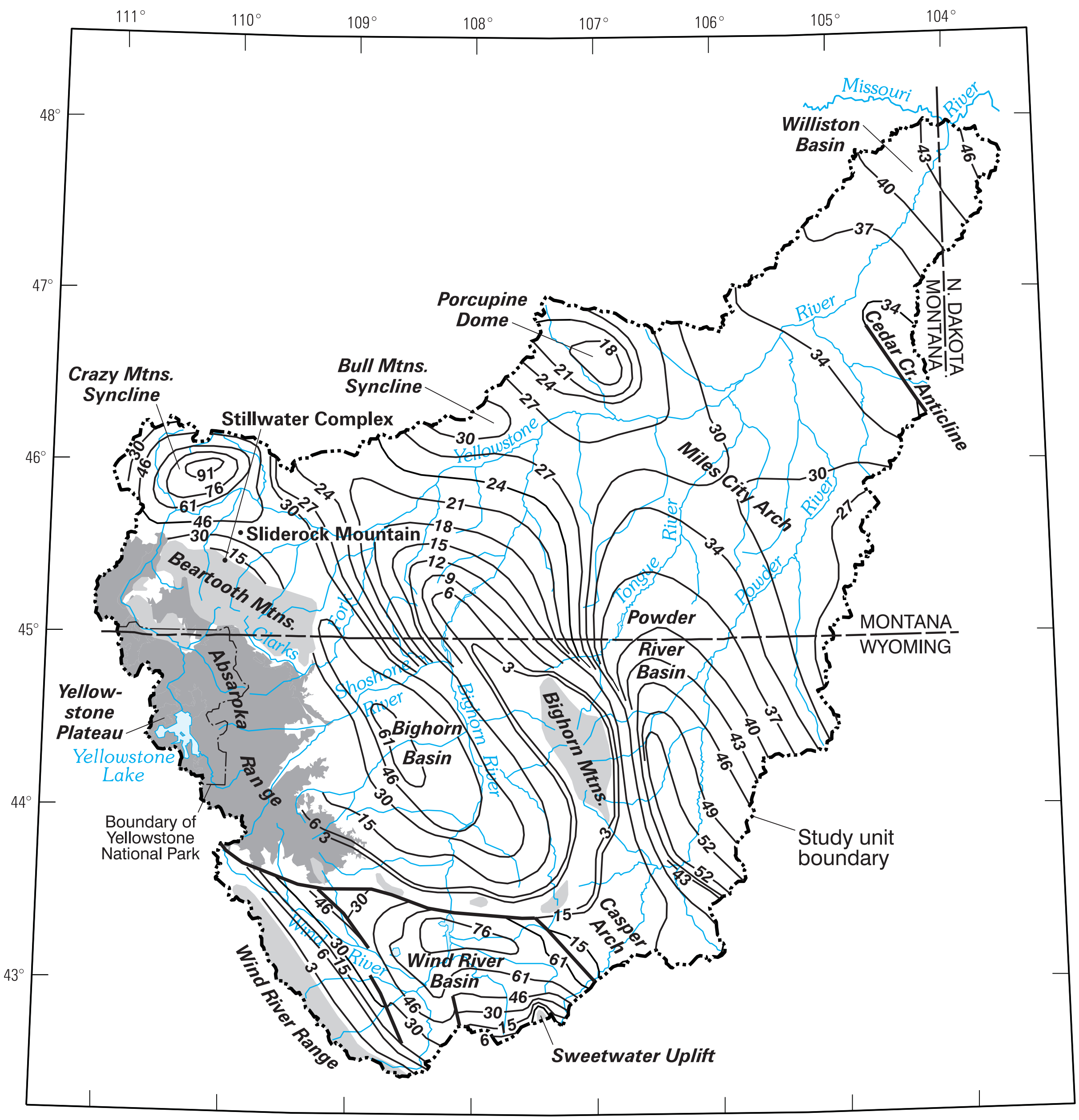


Figure 4. Continued.



Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-area Conic projection
Standard parallels 29°30′ and 45°30′

0 20 40 60 80 100 KILOMETERS
0 20 40 60 80 100 MILES

Geology modified from Jensen, 1972

EXPLANATION

Precambrian crystalline rocks exposed

Absaroka-Yellowstone volcanic area

Line of equal depth, in hundreds of meters

Major fault line

Figure 5. Generalized depth to Precambrian basement structure, Yellowstone River Basin, Montana, North Dakota, and Wyoming.

containing mineralized areas, crops out over an area about 50 km long and up to 8 km wide (Page, 1977). The parent magma of the complex was intruded as a horizontal sill into sedimentary rocks that were metamorphosed to hornfels. After crystallizing, the complex was tilted, beveled by erosion, later deformed during the Laramide orogeny, and today stands nearly vertical (Simons and others, 1979). As a result of the tilting, a 5,500-m thick section of layered igneous rocks is exposed (Elliott and others, 1993, p. 9).

The Bighorn Mountains (fig. 5) represent a major structural arch whose crystalline core is bounded and transected by faults. The northern part of the structural arch plunges northwesterly at a low angle (Van Gosen and others, 1996). The Bighorn Mountains are bounded on the north by a narrow, northwest-trending zone composed of a series of northeast-trending, normal faults (Blackstone, 1975). Along their eastern margin, the Bighorns have been displaced eastward along low-angle thrust faults (Brown, 1993). The northern part of the Bighorn Mountains lies on the upthrown side of an east-west trending thrust fault, and the southern part lies on the upthrown side of a high-angle fault trending northeast-southwest (Blackstone, 1993). The crystalline rocks remain buried beneath Paleozoic sedimentary rocks throughout much of the northern Bighorn uplift, including the Pryor Mountains.

Although they are topographically distinct from the Bighorn Mountains, the Pryor Mountains (fig. 2) are the northwest extension of the Bighorn structural uplift (Blackstone, 1975). Five tilted fault blocks compose the Pryor Mountains, with each block being uplifted highest at its northeast corner (Blackstone, 1975). Block boundaries include faults and faulted or unfaulted folds (Van Gosen and others, 1996).

The Owl Creek Mountains (fig. 2) are a narrow, east-west trending, asymmetrical anticline. The north flank of the uplift is overlain by northward-dipping Paleozoic sedimentary rocks, and the southern flank is overlain by Tertiary strata. Concealed by the Tertiary deposits are Paleozoic and Mesozoic rocks that are overthrust by Precambrian crystalline rocks that form the core of the uplift (Hausel, 1989).

The Wind River Range (fig. 5) is an asymmetrical anticline having a Precambrian core of high-grade metamorphic and igneous rock. Along its eastern flank, Paleozoic and Mesozoic strata dip eastward, but along the northern and northeastern flanks the strata are folded and faulted. Major, moderately dipping faults bound the range on the south and west and overthrust the Precambrian igneous and metamorphic rocks above basin-filling sedimentary strata. The crystalline core of the range is a complex of migmatite, felsic orthogneiss, and paragneiss intruded by quartz diorite to granite plutons (Hausel, 1989). The southern margin of the early crystalline complex is intruded by a granodiorite batholith that also intrudes the gneiss complex adjacent to the South Pass greenstone belt (Hausel, 1991).

Structural Basins

The names of several structural basins are identical with names of surface drainage basins. In most cases the geographic extent of both same-named basins is roughly equivalent. However, the reader is alerted to a substantial difference in the geographic extent of the hydrologic Powder River Basin (entirely within the study unit) and the structural basin of that same name (extending well beyond the study unit on its southeastern margin).

The Bighorn Basin is asymmetric, with its western flank being the steepest and its axis trending northwest-southeast; sedimentary rocks of the structural basin exceed a maximum thickness of 7,200 m along the basin axis southeast of Cody (Blackstone, 1993). On the east, the Bighorn Mountains are thrust westward onto basin sedimentary rocks at the northern and southern ends of the mountain range (Lageson and Spearing, 1988). Major deformation produced a zone of folded rocks around the flanks of the basin (Blackstone, 1988); some of these structural features are important reservoirs of oil and gas.

The Crazy Mountains Basin (or Syncline) (fig. 5) is a northwesterly trending structural basin filled with sedimentary, intrusive, volcanic, and volcaniclastic rocks (Elliott and others, 1993). Subsidence and deposition were greater in the western part of the basin (Roberts, 1963). The deposits attain a maximum thickness of about 9,000 m.

The Powder River Basin (fig. 5) is a gentle syncline between the Bighorn Mountains on the west and the Black Hills of South Dakota on the east (not shown on fig. 5) (Berryhill and others, 1950). The Miles City Arch separates the Powder River and Williston structural basins (fig. 5). The southern and southeast parts of the structural basin lie outside the study unit. The Powder River basin’s axis trends northwest-southeast and lies near its more steeply dipping western flank along the Bighorn Mountains and the Casper Arch (Blackstone, 1993). The maximum thickness of sedimentary rocks in the Powder River Basin exceeds 5,400 m along the basin axis northeast of Casper.

The Williston Basin (fig. 5) is approximately oval shaped with the axis oriented north-northwest to south-southeast. The deepest part of the structural basin is in northwestern North Dakota, about 50 km east of the study unit. The maximum thickness of sedimentary rocks is about 5,200 m (Busby and others, 1995). The dip of the sedimentary strata varies, but is typically about 0.3 percent (Crosby and Klausing, 1984). The Cedar Creek anticline protrudes into the southwestern part of the Williston Basin and is the most pronounced positive structural feature in the northeastern YRB.

The Wind River Basin (fig. 5) is an east-west trending asymmetrical basin bounded by the Owl Creek Mountains to the north, the Wind River Range to the west, the Casper Arch to the east, and the Sweetwater uplift to the south. It is surrounded by folded and faulted Paleozoic and Mesozoic rocks on the flanks of the uplifts. On its northern and eastern margins, Precambrian blocks have been thrust south and west, respectively, to overhang the Paleozoic, Mesozoic, and Cenozoic sediments filling the basin (Brown, 1993). The deepest parts of the structural basin lie in the north, adjacent to the Owl Creek Mountains, where sedimentary rocks reach a thickness of about 7,600 m (Blackstone, 1993).

Stratigraphy

Sedimentary rocks in the study unit range from the Cambrian to Quaternary Systems, and include both continental and marine deposits. The outcrops of most units are shown on the individual State geologic maps for Montana (Ross and others, 1955; Raines and Johnson, 1996), North Dakota (Clayton, 1980), and Wyoming (Love and Christiansen, 1985; Green and Drouillard, 1994). A generalized composite of the outcrop maps is shown in figure 6.

The distribution and thickness of the geologic units are controlled largely by the tectonic events that produced the basins, uplifts, and associated faults (Whitehead, 1996). Diagrammatic sections illustrating the association between generalized stratigraphy and the principal structural features are shown in figure 7.

A generalized correlation chart for Paleozoic, Mesozoic, and Cenozoic rocks (fig. 8) shows that the distribution of geologic units varies considerably across the YRB. Differences in nomenclature between parts of the YRB further complicate the discussion of stratigraphy. The following sections provide an overview of the stratigraphy of the study unit, but for individual description of many of the geologic units shown in figure 8, the reader is referred to the sources from which that figure was compiled.

Paleozoic Rocks

The Pre-Cretaceous rocks (Cambrian through Jurassic Systems) frequently are not differentiated with respect to series, groups, or formations on the State geologic maps, and are exposed in only 8.3 percent of the study unit. Where deeply buried, as they are in structural basins, these rocks are beyond the scope of the NAWQA study-unit investigations that focus on shallow ground water and surface water. Paleozoic rocks are exposed at the land surface in discontinuous, often small, and irregular areas within the YRB. These outcrops generally are on the flanks of uplifts or where erosion has exposed the folds of an anticline (Whitehead, 1996).

The Cambrian sequence is exposed in less than 1.4 percent of the study unit. A general decrease in carbonate rocks and an increase in sandstone and conglomerate exists from west to east across the YRB (Lochman-Balk, 1972).

Ordovician strata are exposed in less than 1 percent of the study unit and reach a maximum thickness greater than 240 m in the northeastern extremity of the YRB. Directly overlying Cambrian rocks in much of the YRB, is the Bighorn Dolomite that forms nearly all of the 150 m of Ordovician rocks present in much of northern Wyoming (Boyd, 1993). All Ordovician Formations are absent in the southeastern Powder River Basin (Boyd, 1993; Foster, 1972).

Silurian strata reach a maximum thickness within the study unit of about 220 m at the YRB outlet area, and thin steadily to the southwest (Gibbs, 1972, p. 87). Nowhere in the YRB are Silurian strata exposed at the surface. Devonian rocks are exposed over less than 1 percent of the study unit. The Devonian System is absent in the southeastern part of the study unit, generally thickens toward the northwest and northeast, and reaches a maximum thickness of about 430 m at the YRB outlet area (Baars, 1972, p. 94).

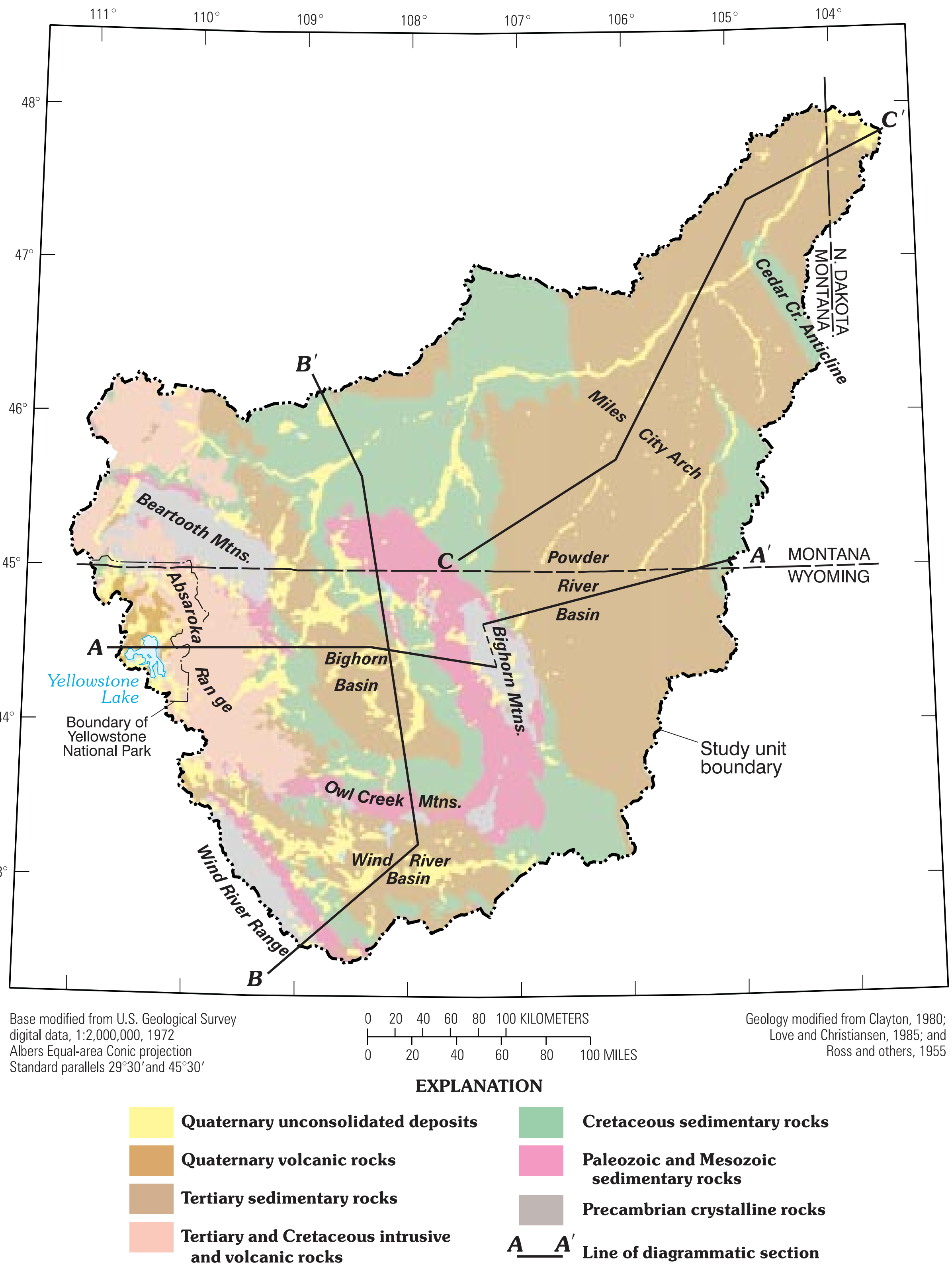


Figure 6. Generalized geology, Yellowstone River Basin, Montana, North Dakota, and Wyoming.

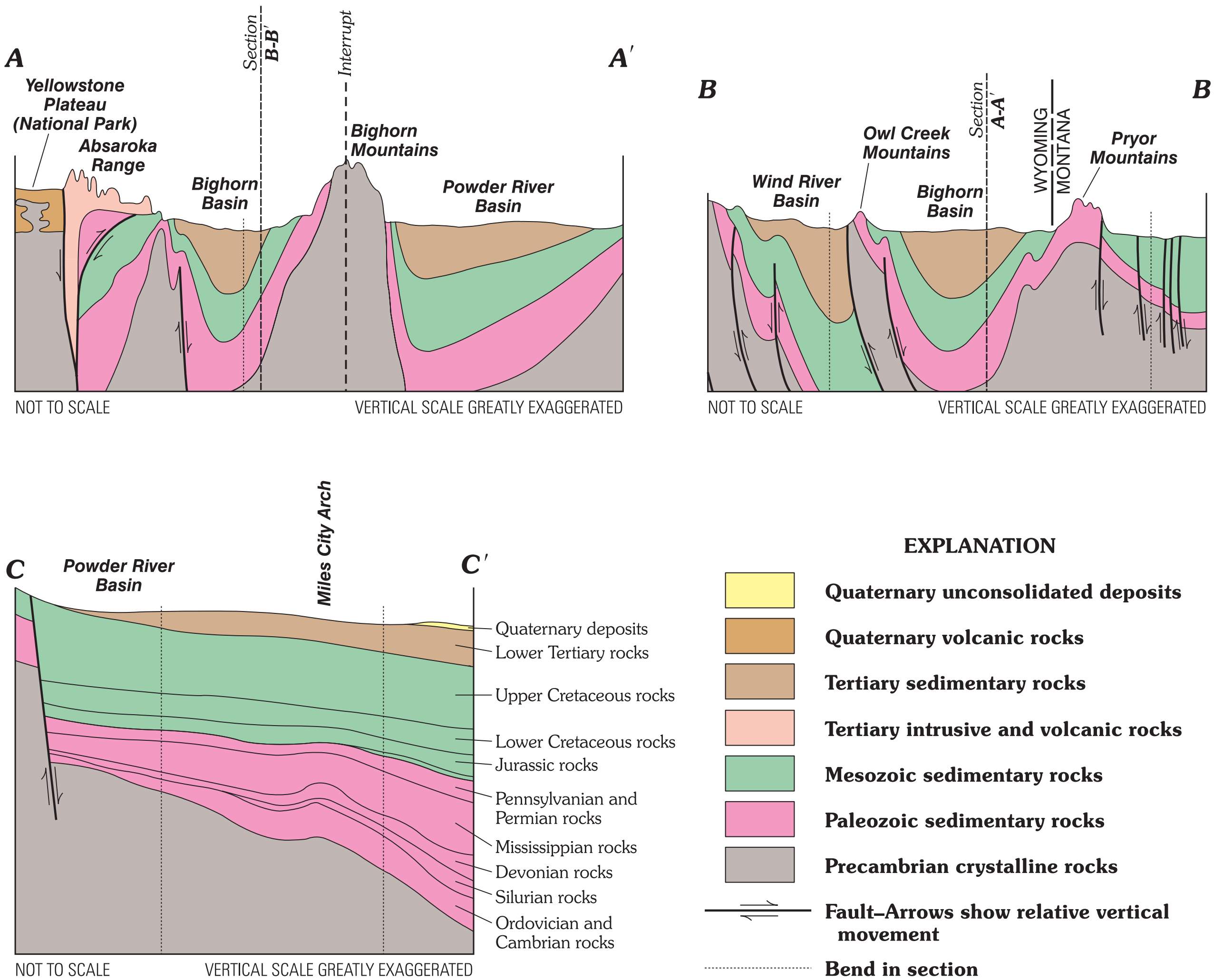


Figure 7. Diagrammatic sections showing principal geologic structures and groupings of geologic units, Yellowstone River Basin. Lines of sections shown in figure 6.

A thick carbonate sequence of Mississippian strata covers the structural basins of the study unit, ranging in thickness from about 60 m in the southeast to about 760 m in the YRB outlet area. In the Montana part of the YRB, thickness increases northward, whereas in Wyoming, thickness increases northward and westward (Craig, 1972, p. 103). Mississippian rocks are exposed over less than 3.5 percent of the study unit. Lower Mississippian rocks include lower and middle sections of the widespread Madison Limestone, or equivalently, the Lodgepole and Mission Canyon Limestones of the Madison Group (Boyd, 1993).

The Pennsylvanian System is less than 100 m thick in the northwestern YRB, thickens gradually to the south and southeast to an average thickness of about 150 m over the southern half of the study unit, and exceeds 210 m of thickness in the southern Powder River Basin (Mallory, 1972, p. 115). Pennsylvanian rocks are exposed over less than 0.5 percent of the study unit.

Permian rocks are exposed over less than 2.5 percent of the study unit. Lower Permian rocks are present only in the southern part of the Powder River Basin and northeastward from there along the eastern edge of the YRB (Boyd, 1993; Rascoe and Baars, 1972). In total, the Permian sequence is thickest in the southeastern part of the study unit, where it exceeds 160 m, and thins to the northwest, wedging out altogether along most of the northwestern margin of the YRB (Rascoe and Baars, 1972, p. 146).

Triassic and Jurassic Systems

Like the Paleozoic rocks that underlie them, the Triassic and Jurassic Systems are downwarped and deeply buried in the structural basins (Whitehead, 1996). The Triassic System is an eastward-thinning wedge that covers most of the YRB, has a maximum thickness of about 600 m in the southwestern Wind River Basin, and is absent along the northwestern margin of the study unit (MacLachlan, 1972, p. 169). Triassic rocks are exposed over less than 2 percent of the study unit.

The Nugget Sandstone (fig. 8) overlies the Upper Triassic rocks of the Wind River Basin to a maximum depth of about 120 m, but is absent elsewhere in the study unit (MacLachlan, 1972, p. 174). These coarse-grained, crossbedded eolian sandstones may be Upper Triassic in age but, according to Picard (1993), are probably Lower Jurassic.

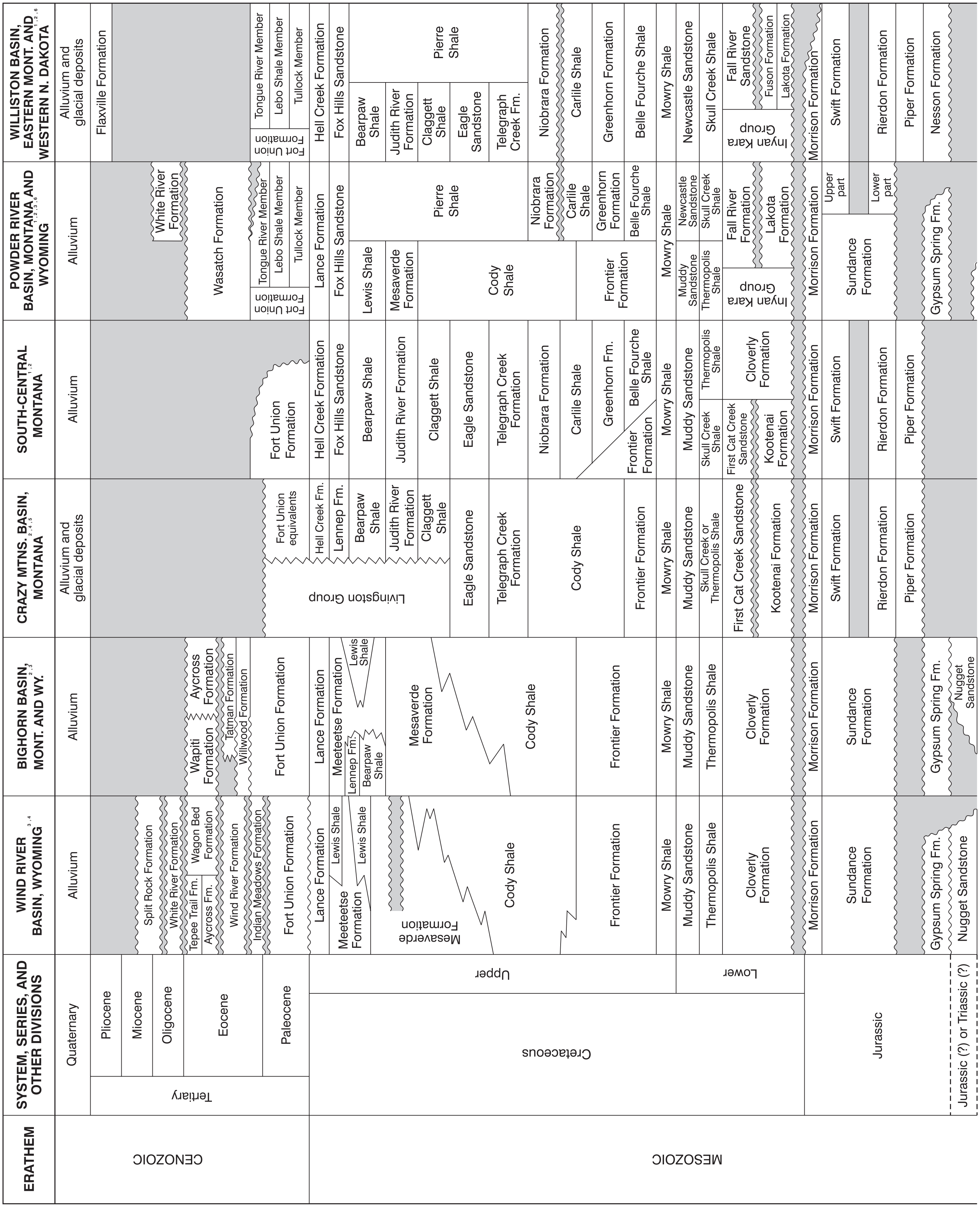
Jurassic rocks are exposed over less than 1 percent of the study unit. The Jurassic sequence covers all the structural basins of the study unit, is thickest (about 380 m) near the YRB outlet and at the northwest end of the Wind River Range, and thins toward the southeastern and northwestern parts of the YRB (Peterson, 1972, p. 180).

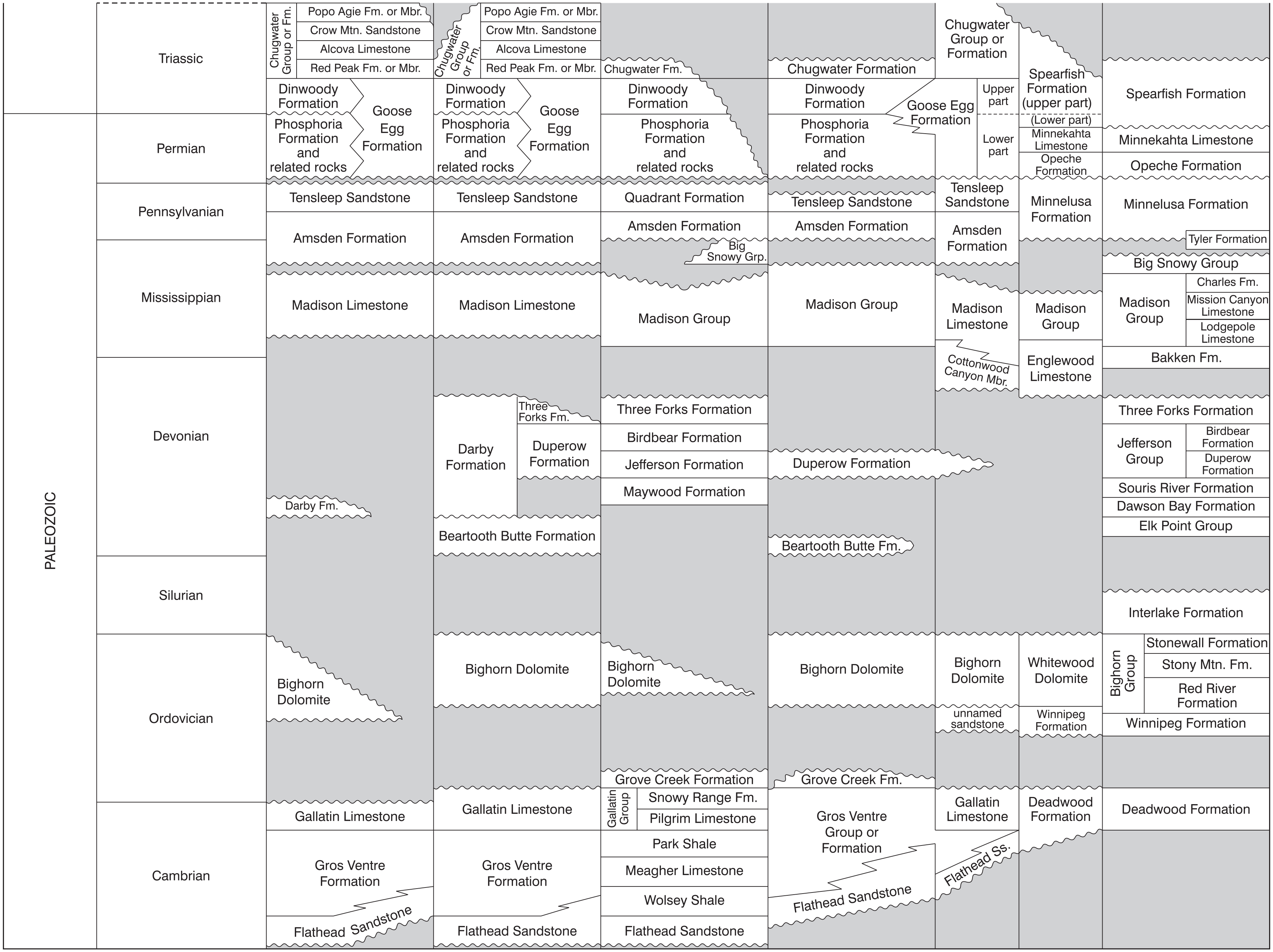
Cretaceous System

Sedimentary rocks of the Cretaceous System extend over most of the plains and basins of the YRB, but are deeply buried at many locations. Where these rock units crop out, as they do in about 23 percent of the study unit, they usually are tilted and often beveled by erosion. The Lower Cretaceous rocks are thickest in the west and northwest (about 240 m), thin to generally less than 120 m in the east and southeast, and are absent only where removed by erosion on uplifts (McGookey and others, 1972; Steidtmann, 1993). Lower Cretaceous rocks generally outcrop in the YRB only on the flanks of uplifts and anticlines, or where displaced upward along faults.

The Upper Cretaceous rocks exceed 2,400 m in thickness in the southern Powder River and eastern Wind River basins, generally range between 1,200 and 2,400 m elsewhere, but are thinner in the southwestern and northeastern corners of the study unit (McGookey and others, 1972, p. 207). In ascending order, the Upper Cretaceous stratigraphic sequence in much of the YRB is the Mowry Shale, Frontier Formation, Cody Shale, Mesaverde Formation, Lewis Shale, Fox Hills Sandstone, and the Lance Formation. In the Bighorn and Wind River Basins, the marine Lewis Shale and nonmarine Meeteetse Formation interfinger and together occupy the interval between the Mesaverde and Lance Formations (fig. 8).

In the northwestern YRB is a thick Upper Cretaceous sequence of rocks consisting chiefly of volcanic debris that is named the Livingston Group (Roberts, 1972). The group is composed of four nonmarine formations: a basal unit of siltstone and sandstone, overlain by a unit of alternating beds of siltstone and sandstone, a unit of largely mudstone, and an upper unit of sandstone and conglomerate (Roberts, 1972).


ERATHEM
SYSTEM, SERIES, AND OTHER DIVISIONS
WIND RIVER BASIN, WYOMING[3,4]
BIGHORN BASIN, MONT. AND WY.[2,3]
CRAZY MTNS. BASIN, MONTANA[2,4,5]
SOUTH-CENTRAL MONTANA[1,2]
POWDER RIVER BASIN, MONTANA AND WYOMING[1,2,3,5,6]
WILLISTON BASIN, EASTERN MONT. AND WESTERN N. DAKOTA[1,2,6]
CENOZOIC
MESOZOIC
Tertiary
Quaternary
Pliocene
Miocene
Oligocene
Eocene
Paleocene
Cretaceous
Upper
Lower
Jurassic
Jurassic (?) or Triassic (?)
Alluvium
Split Rock Formation
White River Formation
Tepee Trail Fm.
Aycross Fm.
Wagon Bed Formation
Wind River Formation
Indian Meadows Formation
Fort Union Formation
Lance Formation
Meeteetse Formation
Lewis Shale
Lewis Shale
Mesaverde Formation
Cody Shale
Frontier Formation
Mowry Shale
Muddy Sandstone
Thermopolis Shale
Cloverly Formation
Morrison Formation
Sundance Formation
Gypsum Spring Fm.
Nugget Sandstone
Alluvium
Wapiti Formation
Aycross Formation
Tatman Formation
Willwood Formation
Fort Union Formation
Lance Formation
Meeteetse Formation
Lennep Fm.
Bearpaw Shale
Lewis Shale
Mesaverde Formation
Cody Shale
Frontier Formation
Mowry Shale
Muddy Sandstone
Thermopolis Shale
Cloverly Formation
Morrison Formation
Sundance Formation
Gypsum Spring Fm.
Nugget Sandstone
Alluvium and glacial deposits
Fort Union equivalents
Livingston Group
Hell Creek Fm.
Lennep Fm.
Bearpaw Shale
Judith River Formation
Claggett Shale
Eagle Sandstone
Telegraph Creek Formation
Cody Shale
Frontier Formation
Mowry Shale
Muddy Sandstone
Skull Creek or Thermopolis Shale
First Cat Creek Sandstone
Kootenai Formation
Morrison Formation
Swift Formation
Rierdon Formation
Piper Formation
Alluvium
Fort Union Formation
Hell Creek Formation
Fox Hills Sandstone
Bearpaw Shale
Judith River Formation
Claggett Shale
Eagle Sandstone
Telegraph Creek Formation
Niobrara Formation
Carlile Shale
Greenhorn Fm.
Belle Fourche Shale
Frontier Formation
Mowry Shale
Muddy Sandstone
Skull Creek Shale
Thermopolis Shale
First Cat Creek Sandstone
Kootenai Formation
Cloverly Formation
Morrison Formation
Swift Formation
Rierdon Formation
Piper Formation
Alluvium
White River Formation
Wasatch Formation
Fort Union Formation
Tongue River Member
Lebo Shale Member
Tullock Member
Lance Formation
Fox Hills Sandstone
Lewis Shale
Mesaverde Formation
Pierre Shale
Cody Shale
Niobrara Formation
Carlile Shale
Greenhorn Formation
Belle Fourche Shale
Frontier Formation
Mowry Shale
Muddy Sandstone
Newcastle Sandstone
Thermopolis Shale
Skull Creek Shale
Inyan Kara Group
Fall River Formation
Lakota Formation
Morrison Formation
Sundance Formation
Upper part
Lower part
Gypsum Spring Fm.
Alluvium and glacial deposits
Flaxville Formation
Fort Union Formation
Tongue River Member
Lebo Shale Member
Tullock Member
Hell Creek Formation
Fox Hills Sandstone
Bearpaw Shale
Judith River Formation
Claggett Shale
Eagle Sandstone
Telegraph Creek Fm.
Pierre Shale
Niobrara Formation
Carlile Shale
Greenhorn Formation
Belle Fourche Shale
Mowry Shale
Newcastle Sandstone
Skull Creek Shale
Inyan Kara Group
Fall River Sandstone
Fuson Formation
Lakota Formation
Morrison Formation
Swift Formation
Rierdon Formation
Piper Formation
Nesson Formation



Compiled from [1] Anna, 1986; [2] Balster, 1980; [3] Love and others, 1993; [4] McGookey and others, 1972; [5] Robinson, 1972; and [6] Whitehead, 1996

Figure 8. Generalized correlation chart of Paleozoic, Mesozoic, and Cenozoic rocks, Yellowstone River Basin.

Tertiary System

A thick sequence of sedimentary rocks of Tertiary age unconformably overlies the eroded Cretaceous surface in most of the plains and basins of the study unit. Tertiary sedimentary rocks are exposed over about 43 percent of the study unit, and Tertiary volcanic rocks are exposed over nearly 8 percent. The Paleocene Fort Union Formation, Eocene Wasatch, Willwood, or Wind River Formations, and Oligocene White River Formation are widely found in the Tertiary stratigraphic sequence. Units other than the Fort Union Formation or equivalents are absent in many places, and Tertiary volcanic rocks are present chiefly in the vicinity of the Absaroka volcanic field.

Paleocene and Eocene sedimentary rocks consist chiefly of sandstone, siltstone, claystone, with interbedded coal and lignite (Whitehead, 1996). The Paleocene Fort Union Formation is widespread in three of the major structural basins of the study unit: the Bighorn, Powder River, and Wind River Basins. However, in the Eocene interval the different basins of the study unit display contrasting stratigraphy (fig. 8).

The Eocene rocks of the Absaroka volcanic field were named the Absaroka Volcanic Supergroup (Smedes and Prostka, 1972) because three stratigraphic groups are included: in ascending order, the Washburn Group, Sunlight Group, and Thorofare Creek Group. No column for this volcanic field is included in the generalized correlation chart (fig. 8); the reader is referred to Sundell (1993) for a recent overview. The Washburn Group is the oldest part of the volcanic deposits and makes up much of the northern Absaroka Range. Farther south, it is overlain by rocks of the Sunlight Group. Due to the lack of regional marker beds, correlations between different areas of the Absaroka volcanic field are not well established. The stratigraphy is greatly complicated by multiple source areas, reworking, and post-depositional deformation including regional tectonism, volcanism, and mass movements (Sundell, 1993).

Oligocene and Miocene sedimentary rocks consist mostly of semiconsolidated claystone, siltstone, sandstone, with some conglomerate (Whitehead, 1996). The Oligocene White River Formation is widespread in the south and eastern parts of the study unit, but is absent in the Bighorn Basin. According to Love and others (1963), at the conclusion of the period of Miocene deposition, only scattered knobs of Precambrian basement rocks protruded from the thick blanket of sedimentary rocks. Within the study unit, the Miocene is represented primarily by the Split Rock Formation in the Wind River Basin and the Colter Formation on the Yellowstone Plateau.

Quaternary System

A great variety of Quaternary deposits occur within the study unit, including eolian, fluvial, glacial, landslide, and volcanic deposits. Valley-fill deposits consisting of unconsolidated gravel, sand, silt, and clay occur adjacent to most of the larger streams of the study unit (Whitehead, 1996). Although unconsolidated deposits, commonly being quite permeable and often located along streams, are likely to be important for understanding hydrology and water quality, they are not further discussed in this section because their spatial heterogeneity is so great that brief treatment is of minimal value. Of the consolidated Quaternary deposits, particular attention is given to the Quaternary volcanic rocks composing the Yellowstone Plateau.

The rocks of the Yellowstone Plateau are almost exclusively rhyolites and basalts, with the rhyolites being greatly predominant (Christiansen and Blank, 1972). The welded ash-flow tuffs that largely compose the outer part of the plateau are separated by unconformities into three major ash-flow sheets. The tuffs overlie rocks from the Precambrian through Quaternary Systems, but in the eastern plateau they chiefly overlie Eocene rocks of the Absaroka Volcanic Supergroup. At the center of the plateau, rhyolitic lava flows cover and partly fill the enormous elliptical caldera formed as a result of the eruption of the oldest ash-flow sheet.

Glaciation

The northeastern part of the study unit was subjected to three periods of glaciation that have not been radiometrically dated, but most likely the early Wisconsinan advance more than 20,000 years ago was the most recent glaciation (Clayton and others, 1980). Along the Yellowstone River valley, a high terrace surface (119 m above the river near Glendive, Mont.) converges with the present floodplain in the upstream direction. The two surfaces are only 38 m apart east of Billings, Mont. The upstream convergence of the two surfaces suggests that downcutting of the Yellowstone River was the result of base-level lowering following retreat of the ice sheet that had blocked the northeast-flowing rivers of Montana (Johns and others, 1982).

During one of the glacial advances, the Missouri and Yellowstone Rivers apparently flowed into North Dakota at a point about 18 km south of where the present Yellowstone River crosses that boundary (Clayton and others, 1980). The transport of water and sediment from the upper Missouri River through that relict valley potentially could be reflected in distinctive alluvial ground-water characteristics.

Glacial sediments, other than scattered lag boulders, are found only behind the terminus of the most recent glacial advance into the study unit; there, lag boulders abound and glacial sediment is widely preserved (Clayton and others, 1980). Although about 2.5 percent of the YRB was subjected to continental glaciation (Fenneman and Johnson, 1946), less than 0.5 percent is presently overlain by sediments deposited by continental glaciation (Clayton, 1980).

Alpine glaciation was widespread in the high mountainous areas of the YRB during the Pleistocene Bull Lake and Pinedale Glaciations. During the Pinedale Glaciation, about 13,000 to 30,000 years ago, major ice streams from four source areas converged to form the northern Yellowstone outlet glacier that flowed 60 km down the Yellowstone valley (Pierce, 1979). Ice from the Pinedale icecap on the Yellowstone Plateau also flowed into adjacent basins and out to other glacial termini, some of which were outside the study unit. During the late Pleistocene, mountain glaciers in places extended several kilometers beyond canyon mouths onto basin floors (Mears, 1987). The icecap on the Beartooth uplift was a source area for numerous glaciers, the northern Yellowstone outlet glacier among them (Pierce, 1979).

Although their size and elevation were probably the most important factors affecting the glacial productivity of the source areas, geographic location with respect to incoming storms was also very significant (Pierce, 1979). Many storms probably moved eastward from the Pacific Northwest and dropped great amounts of snow when forced to rise over the icecaps on the Yellowstone Plateau (Pierce, 1979), Beartooth Mountains, and Wind River Range.

Today, only small remnant glaciers are present in the study unit, mostly concentrated in the Beartooth and Wind River Mountains. But glacial and periglacial landforms are quite extensive. Many of the mountain streams flow through U-shaped valleys characteristic of alpine glaciation. Pinedale Till, and Bull Lake Till at locations beyond the maximum limit of Pinedale Glaciation, dominate the lower hillslopes of many mountain valleys. Glacial-outwash terraces stand higher than Holocene stream terraces and present-day floodplains in many stream valleys.

Seismicity

Seismicity of the region, based on earthquake frequency and intensity, was described by Simon (1972). The westernmost section of the study unit has been an area of moderate seismic activity, whereas seismicity in the Bighorn and Wind River Basins has been substantially less (Simon, 1972, p. 50). Substantial areas where no recorded earthquakes have occurred include the Powder River Basin and the Beartooth and Bighorn Mountains. Most of the strong earthquakes in the study area have occurred in the vicinity of Yellowstone National Park, where the Yellowstone caldera lies at the apex of a parabola-shaped zone of seismicity with the axis centered on the eastern Snake River Plain of Idaho (Smith and Braile, 1993). As early as 1871, F.V. Hayden recognized that Yellowstone was at a great volcanic center and, after experiencing several earthquake shocks while camped along Yellowstone Lake, remarked that, “I have no doubt that if this part of the country should ever be settled and careful observations made, it will be found that earthquake shocks are of very common occurrence” (Hayden, 1872). Yellowstone Lake has persisted as a notable area of earthquake swarms (Smith and Braile, 1993).

The significance of seismic activity as a factor potentially affecting water quality is illustrated by the 1959 earthquake and associated landslide in the Madison River valley of Montana (just west of the YRB). That event deposited 32 million m^3 of colluvium on the canyon floor, impounding water behind a 60-m high rock dam it created (Dunne and Leopold, 1978).

Coal and Hydrocarbon Deposits

Most of the coal deposits in the YRB are located in the nearly horizontal Tertiary beds in the structural basins of the Northern Rocky Mountains and Northern Great Plains coal regions. Coal beds within the Paleocene Fort Union Formation are as much as 43 m thick (Flores, 1996). Vast amounts of subbituminous coal are found in extensive beds that are thick enough and near enough to the surface to be considered strippable deposits.

"Coals from the Powder River Basin analyzed for Hazardous Air Pollutants named in the 1990 Clean Air Act Amendments indicate lower * * * [pollutant] content than other coals from within this region and other regions in the United States. Thus, the unique chemical characteristics and thickness of these Fort Union coals make them an important resource for continued and expanded use within current and future environmental constraints" (Flores, 1996).

In the Bighorn Basin, the coal-bearing rocks are exposed around the rim of the basin in a belt 5 to 24 km wide, and consist of the Upper Cretaceous Mesaverde, Meeteetse, and Lance Formations and the Paleocene Fort Union Formation (Berryhill and others, 1950). Coal-bearing formations in the Wind River Basin crop out only around the basin rim and are overlain by thick units of younger, non-coal-bearing rock in the central part (Berryhill and others, 1950). Because coal beds in the Wind River Basin are relatively thin and steeply dipping, they are economically insignificant compared to those in the Bighorn Basin, which are small in comparison with those in the Powder and Tongue River Basins (Peterson and others, 1987). The aggregate thickness of coal in the Fort Union Formation exceeds 90 m in the Powder River Basin (Barlow and others, 1993), but many coal beds are discontinuous, "pod-shaped" deposits (Flores, 1997).

Coal beds also are important reservoirs of methane-rich gas, only recently recognized to represent an enormous "unconventional" energy resource (U.S. Geological Survey, Energy Resource Surveys Program, 1997). Large quantities of water, sometimes saline, are unavoidably produced along with the methane gas. Fractures that permeate coal beds are usually filled with water; the deeper the coal bed, the less water usually present, but the more saline it becomes (U.S. Geological Survey, Energy Resource Surveys Program, 1997).

Hydrocarbon minerals include natural gas and oil, in addition to the coal-bed methane just discussed. Productive reservoirs of hydrocarbon minerals in the Rocky Mountains and Northern Great Plains region are found in strata from the Cambrian through Tertiary Systems (Spencer, 1996). An estimated 99 billion m^3 of gas and 2.5 billion barrels of oil are yet undiscovered, technically recoverable resources in the Bighorn, Powder River, and Wind River Basins (U.S. Geological Survey, 1996a).

In the Powder River Basin, hydrocarbon reservoirs are located mostly in Cretaceous or Paleozoic rocks; reservoirs in the Bighorn Basin are typically in Paleozoic rocks; and in the Wind River Basin, reservoirs in Paleozoic, Cretaceous, and Tertiary rocks are common (DeBruin and Boyd, 1991).

"In general, Paleozoic reservoirs are marine and eolian sandstone and marine carbonate and produce mostly oil and associated gas. Mesozoic reservoirs are mostly marine and fluvial sandstone; the Cretaceous is by far the dominant age of Mesozoic producing rocks. The Cretaceous produces oil and associated gas and non-associated gas. Tertiary reservoirs are dominantly continental, lenticular sandstone and * * * produce mostly gas" (Spencer, 1996).

Paleozoic hydrocarbon reservoirs include a few stratigraphic traps, such as at Cottonwood Creek in the Bighorn Basin, where the Permian Phosphoria Formation and related rocks are the reservoir rocks. The Pennsylvanian Minnelusa Formation also contains many stratigraphically trapped oil reservoirs in the Powder River Basin (DeBruin, 1993). Most of the many important Paleozoic reservoirs in the Bighorn Basin are associated with anticlines around the basin margins. Sandstone reservoirs of the Pennsylvanian Tensleep Sandstone, and carbonate reservoirs of the Phosphoria Formation and Mississippian Madison Limestone are among the major reservoirs of oil and gas (DeBruin, 1993).

In the Lower Cretaceous Series, the Muddy Sandstone hydrocarbon reservoirs are predominantly stratigraphic traps in the Powder River and Wind River Basins (Mullen and Barlow & Haun, Inc., 1993). The Frontier Formation is the major Upper Cretaceous hydrocarbon reservoir in the study unit. Within the YRB, major oil and gas reserves in the Frontier Formation are associated with nearshore marine sandstones and reworked marine sandstones (Doelger and others, 1993). The nearshore marine sandstone of the Frontier Formation is particularly important at the Salt Creek and Teapot fields north of Casper.

In the Tertiary System, the Paleocene Fort Union Formation produces gas in two separate areas of the YRB. Several reservoirs are located in the interior of the Wind River Basin, and sandstone reservoirs associated with coal beds are found in the northeastern Powder River Basin (DeBruin and Boyd, 1991).

Metallic Mineral Deposits

Mineral deposits are the result of specific geologic processes and thus occur only in those geologic environments where those processes have been active (Anderson and others, 1993), or where mineral-enriched material eroded from those deposits has been re-deposited in sufficient concentration to produce secondary enrichment. Only a small fraction of any area is likely to contain recoverable mineral deposits, and such is the case for the study unit, where about 2 percent of the total area lies in the principal areas of metallic mineral deposits (fig. 9). Known, potentially important metallic mineral deposits are found in each of the major structural units of the YRB, except the Williston Basin. Uranium mineralization is particularly widespread, occurring in most of the stratigraphic units (Harris and King, 1993). Important or substantial mineral-deposit areas are discussed separately by structural unit in this section of the report.

Absaroka Volcanic Field

In the Absaroka volcanic field (fig. 9), the geologic environment associated with metallic mineral deposits consists of deeply eroded intrusive centers (volcanic-plutonic complexes), where the plutonic component represents the solidified magma chamber beneath the former volcano (Hammarstrom and others, 1993). Mineralization associated with Absaroka intrusive centers generally occurs as disseminations and stockworks in intensely altered rock and in fractures and veins. Hydrothermal alteration typically produced crudely zoned mineralization around the core of the intrusive complex. Porphyry copper deposits (veinlets and disseminated grains of copper-bearing minerals in plutonic rocks) may occur in the center of the complex (Hammarstrom and others, 1993), often associated with molybdenum, and sometimes traces of gold. Copper-gold skarns and replacement deposits form in limestone when adjacent to the complex; and zinc-lead-silver vein deposits (sulfide minerals containing large concentrations of these, and sometimes gold or other, minerals) occur laterally away from the center along faults and shear zones (Hammarstrom and others, 1993). In addition to the porphyry copper deposits, heavy minerals such as gold may also be found in placer deposits downstream from porphyry districts (Hausel, 1989).

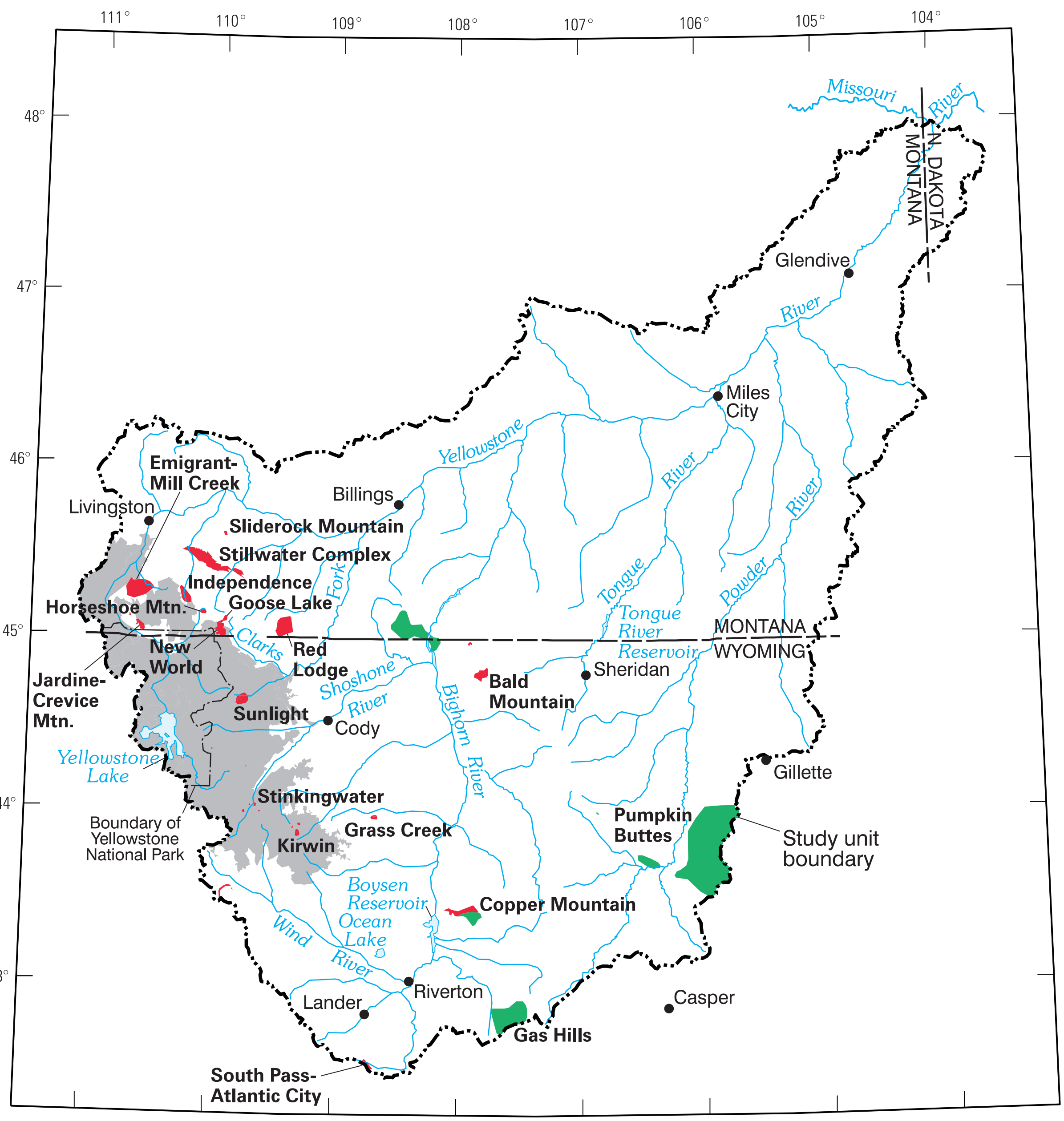
Due to the presence of several large, porphyry copper deposits, the Absaroka Range has definite potential for becoming a metals mining district (Hausel, 1989). Within the Absaroka Range there are four substantially mineralized areas: the Kirwin, New World, Stinkingwater, and Sunlight districts (Nelson and others, 1980).

Several intrusive complexes penetrate the Eocene volcanic rocks of the Kirwin area (fig. 9). The layered, vent-facies volcanic rocks have been domed, hydrothermally altered, and radially fractured (Hausel, 1989). Copper, silver, molybdenum, and gold deposits are known.

The New World district (fig. 9), also known as the Cooke City district, was discovered in the 1860s. It is located in an eruptive center, but uplift and erosion have removed most of the volcanic material and exposed Precambrian gneiss, Paleozoic rocks, and Tertiary intrusive rocks throughout much of the district (Elliott, 1980b). With few exceptions, major ore bodies are localized adjacent to the stocks and mineralization extends outward in irregular metallogenic zones, from copper-gold-silver skarn and replacement deposits near intrusions to distal lead-zinc-silver vein deposits (Hammarstrom and others, 1993b; Hausel, 1989). Many of the copper-gold-silver deposits are gold-bearing skarns that formed in carbonate rocks, in breccia, and along faults (Hammarstrom and others, 1993b). Silver-lead-zinc ores occur in fissure-replacement deposits intruding into Paleozoic limestone south of Cooke City, more than 4 km south of the intrusive centers (Lovering, 1930). Since 1990, considerable exploration and development have focused on five copper-gold-silver deposits in the New World district (Hammarstrom and others, 1993a).

The Stinkingwater district (fig. 9) includes several mineralized porphyries. Mineral deposits in the Stinkingwater area include disseminated sulfide minerals in altered rocks adjacent to granodiorite and dacite intrusive stocks, and fracture-filling veins in adjacent, layered volcanic rocks (Hausel, 1989). Metal zonation is characterized by a central copper-molybdenum zone surrounded by a zone of veins bearing silver, gold, lead, zinc, arsenic, and possibly mercury (Fisher, 1972). Streambed sediments in the vicinity of this mineralized area contain small amounts of gold and mercury (Fisher, 1972).

Both disseminated deposits and vein mineralization occur in the Sunlight district (fig. 9). Disseminated deposits are localized around intrusives and include pyrite in altered zones, chalcopyrite in intrusive rocks, and copper-bearing stockworks (Hausel, 1989). Copper



Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-area Conic projection
Standard parallels 29°30′ and 45°30′

0 20 40 60 80 100 KILOMETERS
0 20 40 60 80 100 MILES

Modified from Bayley and others, 1973; Cole and others, 1982; Czamanske and Zientek, 1985; Elliott and others, 1983; Fisher, 1972; Hammarstrom, 1993; Harris and others, 1985; Hausel, 1989; James, 1946; Lovering, 1930; Nelson and others, 1980; Simons and others, 1979; U.S. Geological Survey and U.S. Bureau of Mines, 1983; and Wedow and others, 1975

EXPLANATION

- Uranium
- Other metals
- Absaroka volcanic field and Yellowstone Plateau

Figure 9. Principal areas of metallic mineral deposits, Yellowstone River Basin, Montana, North Dakota, and Wyoming.

enriched veins tend to be near the stocks, and lead-silver bearing veins are found at distance from the intrusions (Elliott, 1980a). Samples of vein material collected in 1970 from 40 locations in the Sunlight mining region were analyzed spectrographically and showed consistently minor amounts of gold but locally substantial amounts of silver, copper, and lead (Nelson and others, 1980). Results of sampling bedrock and streambed sediment indicate a copper-gold zone associated with syenite stocks in the south and east part of the Sunlight region, and a lead-silver zone in the north and east (Elliott, 1980a).

Beartooth Uplift and Cretaceous Volcanic Centers

Mineral deposits in the Beartooth uplift are of diverse types and metal suites (U.S. Geological Survey and U.S. Bureau of Mines, 1983). Six primary areas of mineral deposits are known in the western Beartooths: the Emigrant-Mill Creek area, Independence (Boulder) district, and Horseshoe Mountain area are associated with Tertiary intrusive rocks; the Goose Lake area is associated with a Cretaceous intrusion; and the Jardine-Crevice Mountain (Sheepeater) district and Stillwater Complex are in Precambrian rocks. In the eastern Beartooths, the Red Lodge chromite district is the primary known mineral area. North of the Beartooth Mountains front, is the Sliderock Mountain area, containing Cretaceous volcanic and intrusive rocks (Elliott and others, 1993).

In the Emigrant-Mill Creek area (fig. 9), numerous small deposits include such metals as copper, molybdenum, gold, silver, lead, zinc, tungsten, bismuth, manganese, and iron. The Emigrant stock and several smaller dikes, sills, and laccoliths intrude Precambrian gneiss and schist, Paleozoic sedimentary rocks, and Tertiary volcanic rocks (Elliott and others, 1983). Hydrothermal alteration, including widespread pyritic alteration, decreased with intensity outward from the stock and produced a zonation of metallic mineralization. Copper and molybdenum are concentrated near the center of the stock, gold is near its periphery, and lead, zinc, and silver occur mostly near or outside the stock periphery (Elliott and others, 1983). The placer gold deposits of Emigrant Creek were a particularly large and productive mineral resource (Hammarstrom and others, 1993).

In the Independence district (fig. 9), an Eocene intrusion into rocks similar to those at the Emigrant stock is associated with a suite of metals also similar to those in the Emigrant-Mill Creek area (Elliott and others, 1983). Zonation of the altered and mineralized rocks is again evident and is typical of porphyry copper systems (Hammarstrom and others, 1993b). The intrusive rocks of the area are more mafic than those of the Emigrant-Mill Creek area, and therefore considered to have less mineral potential for copper and molybdenum (Elliott and others, 1983). Placer gold is present in most of the surrounding streams (Hammarstrom and others, 1993b).

An altered dacite porphyry at Horseshoe Mountain (fig. 9), midway between the Cooke City and Independence districts, has been historically prospected for gold in both lode and placer deposits. Geochemical anomalies for molybdenum, tungsten, precious- and base-metals have been detected in sediments of streams draining this area (Hammarstrom and others, 1993b).

The Goose Lake area (fig. 9), located in the headwaters of the Stillwater River at the northeast corner of the New World district, contains mineralization associated with a locally altered Late Cretaceous syenite stock intruding Precambrian granitic gneiss. The deposit is considered an unusual occurrence of copper-gold-platinum mineralization that is an example of a magmatic segregation deposit associated with alkaline gabbros and syenites (Hammarstrom and others, 1993b). The principal minerals are chalcopyrite and bornite, occurring as disseminations and vein fillings. Shear zones away from the syenite stock also are mineralized (Simons and others, 1979). Copper, gold, silver, platinum, palladium, lead, and tungsten are present.

Gold discovered in placer deposits in 1862 led to discovery of gold-bearing quartz veins at Jardine in 1870. Substantial deposits of gold, arsenic and tungsten are present, as confirmed by geochemical analyses of rock and stream-bed sediment samples (Wedow and others, 1975). Extensively folded Precambrian metasedimentary rocks contain quartz veins and shear zones that are concentrated in two distinct belts, one through Mineral Hill and the other through Crevice Mountain (Hammarstrom and others, 1993b). The geologic setting of the Jardine-Crevice Mountain deposits (fig. 9) is typical of the metasedimentary parts of ancient greenstone belts, and the deposits are similar to other lode gold systems associated with a banded iron formation (Hammarstrom and others, 1993b).

Mineral deposits of the Stillwater Complex (fig. 9) include chromium, nickel, copper, and platinum-group elements (PGE). The deposits are stratiform and exhibit great lateral continuity (Elliott and others, 1983). The nickel-copper deposits are concentrated at the base of the complex as sulfide-rich zones that have been identified as large tonnage, low-grade resources (Zientek, 1993). PGE occur near the base of the complex and also a few thousand meters above the base in a thin, laterally persistent interval of PGE-enriched disseminated sulfide mineralization (Zientek, 1993). The Stillwater Complex contains the largest identified resources of PGE and chromium in the U.S., in addition to major nickel and copper resources (Hammarstrom and others, 1993a). Undiscovered deposits of copper, nickel, chromium, and platinum-group elements are likely to be present in the complex (Zientek, 1993).

Chromite was discovered in the Red Lodge district (fig. 9) in 1916 (James, 1946). The Red Lodge chromite occurs as lenses in masses of serpentinite intruded into granitic gneiss and is exposed at the edges of plateaus at an elevation of about 3,000 m (Simons and others, 1979). The relatively low-grade chromite deposits have been highly metamorphosed, tectonically disrupted, and isolated (Hammarstrom and others, 1993b). The deposits are dissimilar from the stratiform deposits in the Stillwater Complex (James, 1946). The mineral resources remaining in this district are relatively small, many deposits having been completely mined out.

The Sliderock Mountain area (fig. 9) features a diorite stock surrounded by lahar deposits, andesite flows, and flow breccias. Concentrically zoned hydrothermal alteration and geochemical anomaly patterns indicate the presence of a shallow subsurface porphyry copper-gold deposit (Hammarstrom and others, 1993b). Silver, lead, zinc, and molybdenum also are present.

Bighorn, Owl Creek, and Pryor Mountains

The Precambrian granites and gneisses of the Bighorn Mountains are not considered likely hosts for major precious metal occurrences, but the possibility cannot easily be dismissed (Hausel, 1989). The known precious metal deposits are associated with mafic dikes, veins, and shear zones in the Precambrian core and with core debris in placers in the overlying Cambrian Flathead Sandstone. In the Bald Mountain area (fig. 9), mineral-enriched conglomerates in the Flathead Sandstone contain gold and other heavy minerals, such as ilmenite, magnetite, zircon, and monazite. Other minor deposits of metals in the Bighorn Mountains contain tungsten, silver, manganese, copper, and gold in quartz veins (Hausel, 1989); and numerous small deposits of uranium and vanadium are known in the Little Mountain area (Van Gosen and others, 1996).

In the eastern Owl Creek Mountains (fig. 2), Precambrian metamorphic rocks are exposed in the Copper Mountain district (fig. 9), which includes several known mineralized areas. In the western end of the district, a vein bearing sporadic sulfides and gold represents a relatively small deposit. Near the center of the Copper Mountain district, quartz veins and a banded iron formation are known to contain copper, titanium, gold, and silver (Hausel, 1989). In the eastern end of the district, a mafic dike is fractured and quartz veins fill the fractures; both the veins and the dike are mineralized with copper, nickel, gold, and silver (Hausel, 1989). Also at Copper Mountain, uranium mineralization occurs in the Eocene Tepee Trail Formation and in altered rocks, breccia zones, and fractures in the underlying Precambrian rocks (Yellich and others, 1978).

Numerous uranium-vanadium deposits were discovered in the Pryor Mountains (fig. 2) during 1955-58 (Van Gosen and others, 1996). These deposits are mostly small and are hosted by shallow collapse structures in the upper third of the Madison Limestone. The mineral deposits are found mostly within vugs, open fractures, and the most permeable cavern-fill materials (Van Gosen and others, 1996).

Bighorn and Powder River Basins

In the Bighorn Basin, titaniferous black sandstone deposits, hosted primarily in the Upper Cretaceous Mesaverde Formation, are found in several locations, with the Grass Creek deposit (fig. 9) being the largest high-grade deposit in Wyoming (Hausel, 1993). These deposits contain abundant heavy minerals, including zircon, monazite, and gold, in addition to titanium-bearing minerals (Hausel, 1989).

Uranium deposits (fig. 9) of economic significance in the Powder River Basin occur primarily in the Wasatch Formation of Tertiary age (Hausel, 1982). Most economic uranium deposits in the YRB are found in arkosic Eocene and Paleocene sandstones and conglomerates of continental origin, in which uranium minerals coat the grains and partly fill the interstices (Butler, 1972). Mineralization dominantly occurs as “roll-front” deposits located at contacts between oxidized (altered) and reduced (unaltered) zones (Hausel, 1982). Uranium, being soluble in the oxidized state but not in the reduced state, is readily leached from the oxidized rocks and deposited in zones where geochemical conditions change from oxidizing to reducing (Lowry and others, 1993). Uraniferous tuffaceous units, such as the Oligocene White River Formation, are the probable source of the leached uranium in the Powder River Basin (Harris and King, 1993).

Radium deposits are also found in Tertiary sediments, such as with uranium in concretionary occurrences in the Pumpkin Buttes (fig. 9) area (Harris and King, 1993). Radium is soluble in water, regardless of oxygen availability, but is strongly adsorbed by manganese and iron oxides, so its presence in an oxidizing environment varies with those of the manganese and iron oxides (Harris and King, 1993). There is no present economic interest in radium deposits, as it is readily available from production in nuclear reactors.

Wind River Basin and Wind River Range

In the Gas Hills (fig. 9) uranium district at the southern end of the Wind River Basin, substantial uranium deposits occur in the Wind River Formation of Tertiary age (Hausel, 1982) and may be derived from leached or eroded uranium in the Precambrian granites of nearby mountains (Harris and King, 1993). Wyoming contains more than half of the Nation’s uranium reserves (U.S. Dept. of Energy, Energy Information Administration, 1997), and a substantial percentage is located within the YRB in the Powder River and Wind River Basins.

Alluvial gravels along the Wind River, Little Wind River, and Popo Agie River (not labeled on figures) contain gold, commonly occurring as very fine particles. The largest concentrations known were found in Wind River placer deposits west of Riverton and in a downstream reach now mostly submerged in Boysen Reservoir (Hausel,1989). Other placer deposits of gold and monazite occur in terrace deposits and gravels of Warm Spring Creek (not shown in figures) in the northern Wind River Range (Hausel, 1989). Placer gold also has been found in gravels of several other eastward-flowing streams draining the Wind River Range to the south.

The South Pass-Atlantic City (fig. 9) greenstone belt is known for rich deposits of gold and iron ore. The complexly folded rocks of the greenstone belt extend into the study unit at the southeast end of the Wind River Range (Hausel, 1989). Substantial lode deposits of silver, gold, and copper occur in shear-zone structures and quartz veins. Also, banded iron formation, or taconite, deposits are located along the northwestern flank of the greenstone belt.

Near the greenstone belt, precious-metal bearing Oligocene conglomerates were deposited as a giant alluvial fan at the mountain front. The source of the metals in the Oligocene conglomerate is believed to be a small area of metamorphic rocks cut by veins and probably now buried by strata of the Oligocene White River Formation (Antweiler and others, 1980). Other Tertiary conglomerates in this same general area are known to contain precious metals (Hausel, 1991).

Vegetation

Vegetation is a sensitive indicator of multiple environmental factors, including precipitation, temperature, soil, geology, and wind; in turn, vegetation affects a number of important processes, including snow accumulation, soil moisture depletion, surface runoff, infiltration, and erosion (Knight, 1990). Vegetation input to streams (coarse- particulate organic material) and inputs of chemicals applied to vegetation are additional factors affecting stream quality.

Potential natural vegetation is defined as the ultimate successional stage of the native flora of an area, under the current climatic regime and in the absence of further human modification (Kuchler, 1970). Thus defined, the potential vegetation is partly determined by previous human practices. For example, since settlement, semidesert shrubs seem to have expanded their range into large areas that formerly were steppe (shortgrass prairie), due to overgrazing and trampling by livestock (Bailey, 1995). Plant successional processes alone may not be sufficient to potentially reestablish grasslands in all affected areas. Kuchler (1964) mapped the potential natural vegetation of the U.S. (1:3,168,000 scale), and the part of that map relevant to this report is shown in figure 10. Many of the plant communities generally are distributed in zones corresponding to differences in elevation. This pattern provides the organization for the remainder of this section.

In the alpine meadows that compose about 3 percent of the study unit, tundra vegetation is typical, and trees are nearly absent or stunted where present. Alpine meadows occur mainly above 3,100 m elevation in the YRB (Despain, 1990; Thilenius and Smith, 1985) and are most extensive on the plateaus of the Beartooth uplift. Common plant types in the alpine meadows are

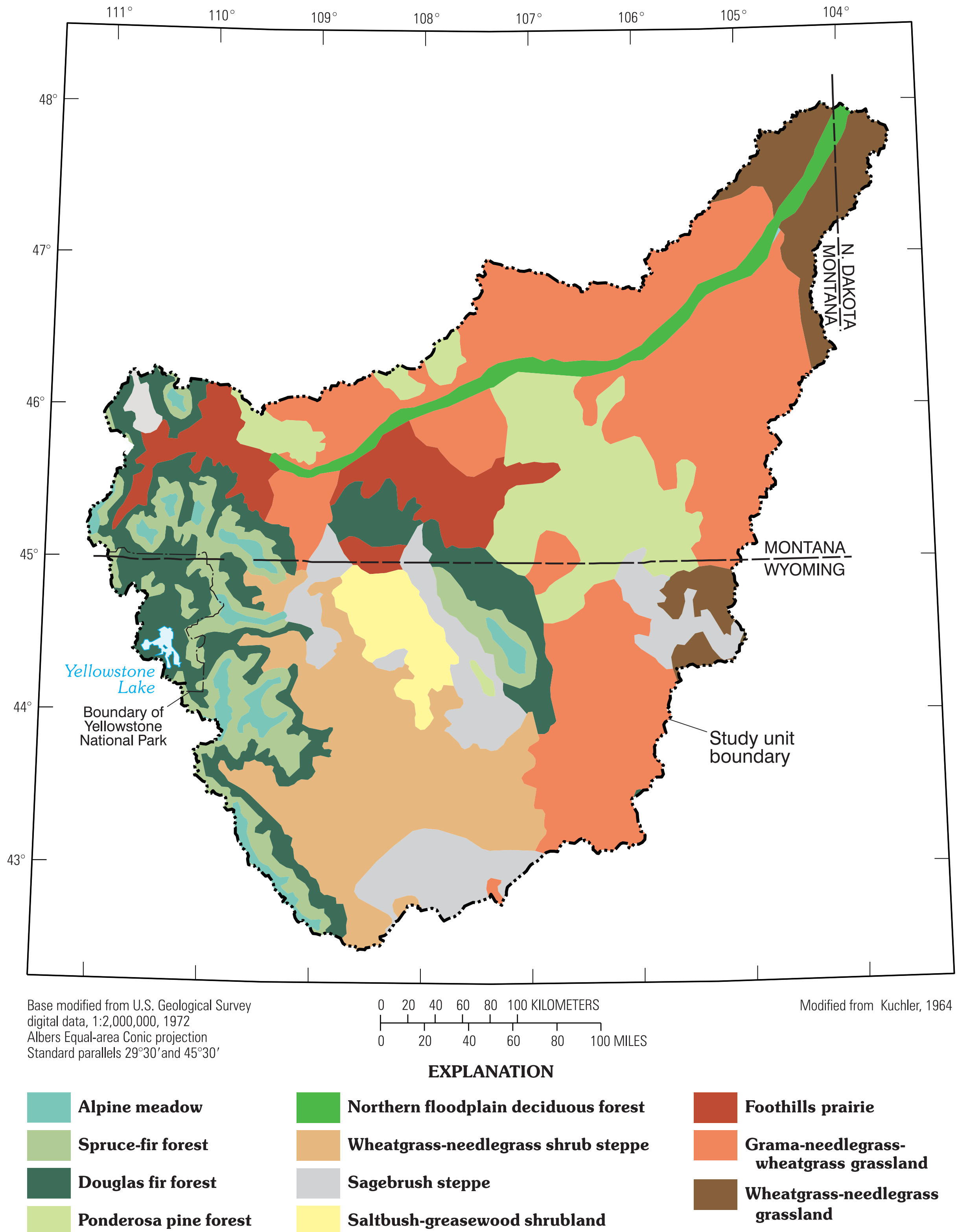


Figure 10. Potential natural vegetation, Yellowstone River Basin, Montana, North Dakota, and Wyoming.

forbs, grasses, sedges, dwarf willows, and prostrate shrubs (Thilenius and Smith, 1985; Marston and Anderson, 1991). These plants are small and close to the ground, where they are protected from the high winds and warmed by longwave reradiation from soil and rocks (Despain, 1990).

The spruce-fir forest is found in the subalpine zone, typically dominated by Engelmann spruce and subalpine fir (Bailey, 1995), but at the upper end of this zone, whitebark pine is dominant (Despain, 1990). Below the subalpine zone lies the montane zone corresponding to Kuchler's (1964) Douglas fir forest (fig. 10). The montane zone characteristically features alternating stands of Douglas fir and ponderosa pine, with the pines dominating on drier, more exposed slopes (Bailey, 1995). Lodgepole pine often is a codominant species at middle elevations (Marston and Anderson, 1991). The distribution of coniferous forest by elevation zone is shown in figure 11. Coniferous forest begins to be the predominant land cover at elevations greater than about 2,100 m. Marston and Anderson (1991) state that an elevation of about 2,130 m defines the boundary of the Greater Yellowstone Ecosystem, because this factor exerts such strong control on the structure and function of both aquatic and terrestrial ecosystems in that area.

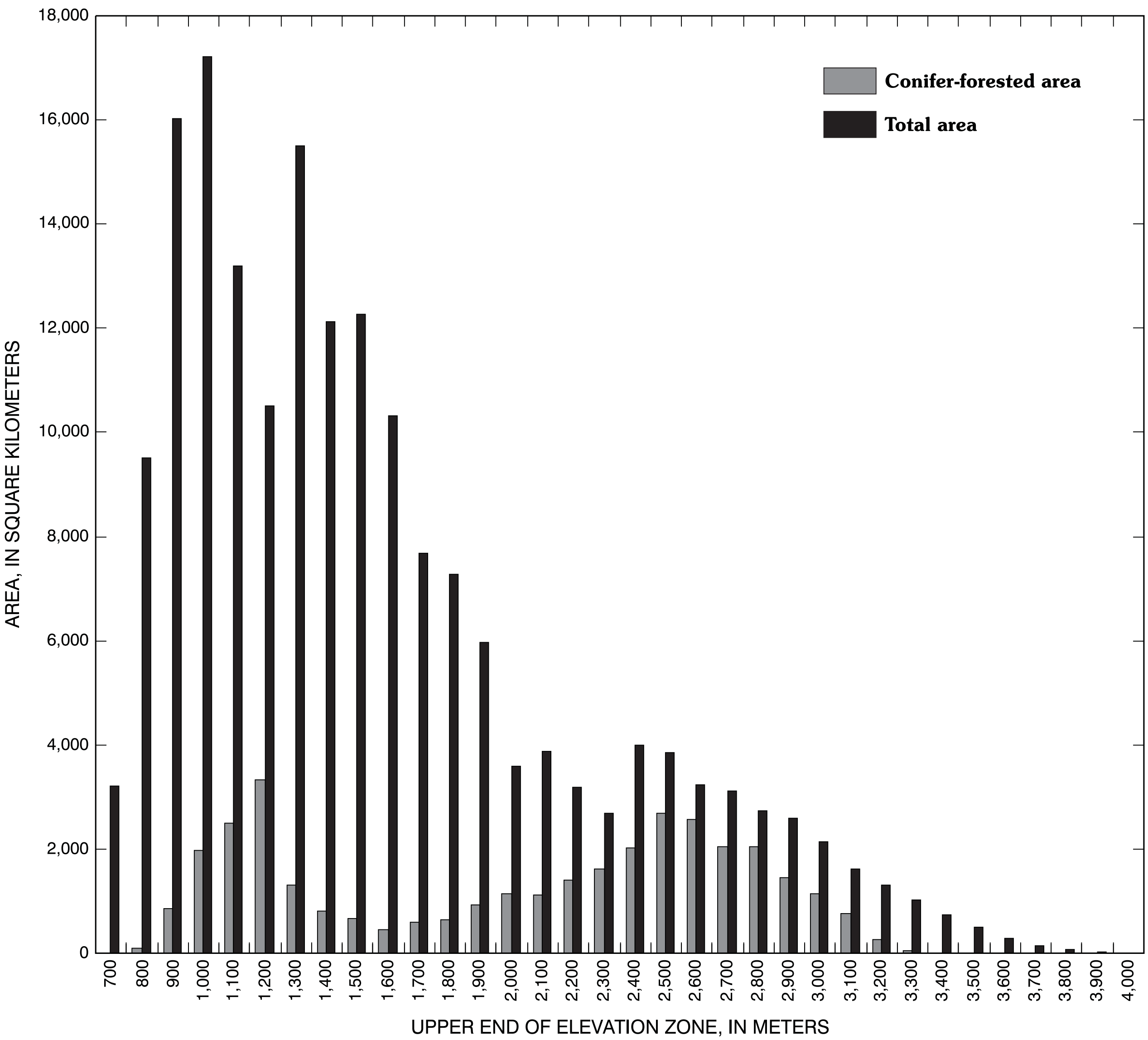


Figure 11. Conifer-forested and total area, by elevation zone, in the Yellowstone River Basin.

In addition to elevation, moisture gradients and disturbance history influence forest types. For example, in subalpine forests of Greater Yellowstone, subalpine fir is more common in moist locations, whereas lodgepole pine and Douglas fir dominate on drier slopes (Despain, 1990). Mountain vegetation zones extend to lower altitudes on wetter east- and north-facing slopes and steppe vegetation extends farther upward on south- and west-facing ones (Bailey, 1995; Marston and Anderson, 1991).

A major disturbance such as fire restarts the long successional process by which vegetation progresses through a series of plant communities toward the climax community (Despain, 1990). Under a natural fire regime, the wildfire return interval in most of the mountain forests in western parts of the YRB is between 200 and 400 years (Despain, 1990; Romme, 1980). Such intervals do not necessarily allow the successional process to culminate. In addition to vegetation disturbance, forest fires produce increased stream discharge, erosion, and sediment transport from severely burned watersheds (Tiedemann and others, 1979). Also, loss of riparian vegetation and woody debris jams increases the risk of serious washouts of organic matter, nutrients, and sediment stored in channels if high-flow events shortly follow the burning of much of a watershed (McIntyre and Minshall, 1996). The large fires of 1988 in the Greater Yellowstone Area burned more than 3,300 km^2 of mostly forested land in the YRB (Minshall and Brock, 1991; Greater Yellowstone Post-Fire Resource Assessment Committee, 1988). The fire-related changes were expected to cause substantial impacts to extensively burned watersheds, but large watersheds (greater than 500 km^2) were only partially burned and principal streams were little affected (Minshall and others, 1989; Minshall and Brock, 1991, p. 126).

Soil and rock types also affect forest communities through nutrient and moisture availability. For example, in the Greater Yellowstone Area, soils formed from andesite have good water-holding capacity and mineral nutrient content, whereas soils formed from rhyolite are coarse textured, with poor water-holding capacity and only one-third the nutrient level of andesitic soils (Despain, 1990). As a result, distinctly different forest communities are found on these contrasting soils: lodgepole pine is persistently dominant in areas underlain by rhyolite flows, whereas spruce-fir communities are usually dominant in old-growth forests on soils formed from andesite (Marston and Anderson, 1991).

In the lower-elevation, open woodlands of the Great Plains Province, ponderosa pine is the dominant species. Such forest lands cover about 6 percent of the study unit, and correspond to the peak in conifer-forested area at about 1,200 m elevation (fig. 11). Grasses, with some sagebrush, typically compose the ground cover and understory in the open woodlands (Bailey, 1995).

Coniferous forests actually cover about 19 percent of the study unit, whereas they potentially would cover about 28 percent under natural conditions (Kuchler, 1964). The major forest types and percentage of YRB forested land they occupy are lodgepole pine (34 percent), ponderosa pine (22 percent), spruce-fir (19 percent), Douglas fir (14 percent), broadleaf hardwoods (6 percent), and pinyon-juniper (4 percent) forests (U.S. Department of Agriculture, Forest Service, 1970).

Steppe is the most widespread vegetation class in the YRB, covering about 44 percent of the study unit, as estimated by comparing data from Bailey (1995) and U.S. Geological Survey (1986). Kuchler's map (1964; fig. 10) shows three categories corresponding to steppe: foothills prairie, grama-needlegrass-wheatgrass grassland, and wheatgrass-needlegrass grassland. The short, typically bunched grasses of the steppes include predominantly grama, needlegrass, and wheatgrass (Bailey, 1995; Kuchler, 1964; Marston and Anderson, 1991). Numerous species of wildflowers bloom during spring and summer, with sunflower among the most prominent (Bailey, 1995). Sagebrush is an important component of the vegetation mosaic in many grassland areas. Prickly-pear cactus apparently was abundant in the early 1800s, as it is today (U.S. Department of the Interior, 1965). Invasive exotic species, such as Russian thistle, are abundant in some locales. Except in moist hollows and valley floors, steppe grasses are usually sparse, with bare soil exposed between the bunches (Bailey, 1995).

Sagebrush steppe or semidesert shrub is the dominant vegetation type in about 21 percent of the study unit (compare Bailey, 1995, and U.S. Geological Survey, 1986). Kuchler's map (1964; fig. 10) indicates that these shrub lands (wheatgrass-needlegrass shrub steppe, sagebrush steppe, and saltbush-greasewood shrubland) would potentially cover about 25 percent of the study unit. Typically, this vegetation type is a mixture of sagebrush with short grasses, but greasewood is prominent in extensive alkaline areas of the Bighorn Basin (Bailey, 1995). Sagebrush is typically found on well drained sites where most of the precipitation occurs as snowfall, whereas grasslands tend to be found where summer rainfall predominates (Knight, 1990). Other common shrubs include rabbitbrush, bitterbrush, and serviceberry (Marston and Anderson, 1991).

In the YRB, typically narrow riparian zones lie between the aquatic and terrestrial ecosystems and include several fluvial surfaces: channel islands and bars, channel banks, floodplains, and lower terraces on which the vegetation is dominated by deeply rooted plants capable of extracting water from the alluvial aquifer (Goodwin and others, 1997). The riparian vegetation community along a stream controls or influences several important ecologic characteristics, such as availability of habitat, canopy closure above the channel, water temperature, photosynthetic productivity, input of allochthonous resources, benthic invertebrate community composition, stream bank stability, density of coarse woody debris elements, and step size in step-pool channels (Hupp and Simon, 1986; Mihuc and others, 1996; Sweeney, 1992). Riparian vegetation may additionally benefit water quality by filtering sediments and utilizing nutrients (Correll and others, 1992; Knight, 1994). Riparian vegetation communities are highly productive and support an abundance of wildlife (Marston and Anderson, 1991), and domestic livestock also congregate there (Knight, 1994). Concentrations of large ungulates may trample banks and contribute to increased erosion and embeddedness. In contrast, beaver often produce a beneficial effect on water quality through dam building (Knight, 1994). Dams arrest streambed degradation, sedimentation behind the dams allows for greater stream clarity downstream, and enhanced bank storage of water results in higher late-summer streamflow that is beneficial to fish and wildlife.

Riparian vegetation is highly variable in the YRB and may include marsh, meadow, shrublands, and forest communities (Knight, 1994). At higher elevations, sedges, grasses, and short willows dominate the community typically found along headwater streams, but alders and tall willows become more conspicuous along lower mountain streams (Knight, 1994). In the foothills and intermontane basins, the riparian communities generally are dominated by cottonwoods, with aspens, lodgepole pine, and spruces also common (Knight, 1994; Marston and Anderson, 1991). Along many streams of the eastern plains, grasses, rushes, and sedges are dominant plants in herbaceous riparian communities; and black greasewood, common chokecherry, coyote willow, silver buffaloberry, silver sagebrush, and western snowberry are dominant species in shrub riparian communities (Jones and Walford, 1995). The riparian zone along many other lowland streams is typically a woodland community with plains cottonwood being most abundant, and ash, boxelder, willows, and the exotic Russian olive all being common locally (Jones and Walford, 1995; Knight, 1994). The abundance of old-growth cottonwoods appears to be declining in some areas due to flood suppression (Knight, 1994). Cottonwood regeneration is related to flooding and associated creation of bare sand and gravel bars that this pioneer species colonizes. Northern floodplain deciduous forests (fig. 10) occupy about 1 percent of the YRB, mostly as riparian communities along several of the principal streams (not only the Yellowstone River).

Other prominent vegetation in the study unit includes native hay, alfalfa, and seasonal coverage by crops such as small grains, beans, sugar beets, and corn. Agricultural lands are discussed in more detail in a separate section of this report.

Surface Water

The surface-water hydrology of the Yellowstone River Basin is characterized by the physiography of the basin and the flow and quality of its streams. Physiographic characteristics of the basin are important influences on the hydrology. Streamflows are characterized according to the origin of the streams as well as by the time of year. Characteristics of general stream-quality indicators illustrate the overall condition and variability in the quality of the basin surface-water.

Basin Characteristics

The diverse physiography of the YRB is an important factor in determining the surface-water hydrology. From its headwaters at the Continental Divide in northwestern Wyoming, the Yellowstone River flows out of the mountains and across the plains of south-central and eastern Montana to the confluence with the Missouri River in western North Dakota (fig. 12). The mainstem flows through the northwestern and northern parts of the study area only, resulting in an asymmetric drainage network. Most inflow to the mainstem is from the south from four major tributary basins: the Clarks Fork Yellowstone, Wind/Bighorn, Tongue, and Powder Rivers. The higher elevations of the Beartooth Mountains, Wind River Range, Absaroka Range, and Bighorn Mountains are the headwaters of most of the perennial streamflow in the basin (Wahl, 1970). Tributary to the major streams, as well as the mainstem, are many streams that originate in the lower elevations of the basins and plains areas.

Basin relief is large; headwaters elevations exceed 3,900 m above sea level for streams originating in the mountains, while the mouth of the mainstem Yellowstone River is only 564 m above sea level. The mainstem is more than 1,130 km long. The combination of large relief in the mountainous areas and long stream lengths across the basins and plains results in a large range in slopes for the major tributaries. Grading downstream from steep to relatively flat, channel slope of the mainstem ranges from more than 8 m/km in the upper reaches to about 0.6 m/km for the lower 400 km of the river. Mean depth and width increase with distance downstream for many streams in the basin. Leopold and Maddock (1953) demonstrated that for a discharge of given frequency (or an approximation thereof, such as mean annual discharge), those channel dimensions can be approximated as power functions of that discharge at sites along the Powder and Wind/Bighorn River Basins and downstream along the mainstem Yellowstone River.

Streamflow Characteristics

Streamflow characteristics in the YRB (table 1) vary by geographic location, time of year, and degree of human influence. For most streams in the basin with little or no flow modifications, streamflow characteristics can be described by annual streamflow and flow duration at representative locations. For streams where human activities have modified the natural drainage, regulation, diversion, and return flows affect streamflow characteristics to varying degrees. Variations in geography and weather cause severe floods and droughts in the basin. Flows resulting from these extreme hydrologic events affect water quality.

Annual Streamflow

Annual streamflow can be characterized by measures of central tendency, such as the mean, and of variability, such as the coefficient of variation (COV), defined as the standard deviation divided by the mean. Most of the annual streamflow from the YRB originates in the mountainous areas of the upper Yellowstone River and the Clarks Fork Yellowstone River and Wind/Bighorn River Basins. Representing about half of the study unit’s total drainage area, the combined mean annual flows from the upper Yellowstone, Clarks Fork Yellowstone, and Wind/Bighorn Rivers equal about 86 percent of the mean annual flow at the mouth of the basin (table 2). Runoff amounts from the basins and plains areas are lower than those from the mountainous areas. Annual runoff in the YRB ranges from less than 0.25 cm (0.1 in.) in the lower-elevation parts of the Wind/Bighorn River Basin to more than 75 cm (30 in.) in the higher elevations of the Wind River Range and Beartooth Mountains (U.S. Geological Survey, 1970a). Mean annual runoff from the Powder River Basin is less than 2 cm (0.8 in.), even though the drainage area for this major tributary is about 20 percent of the YRB study unit (table 2).

Streams in the mountainous areas of the YRB generally are perennial (Wahl, 1970; Lowham, 1988). Most of the flow in mountain streams is from snowmelt runoff. Annual streamflows in the mountainous areas are dominated by a single snowmelt peak of moderate duration during late spring/early summer with low variability in daily mean discharge throughout the year (figs. 13 A and F). Variabilities in annual flows in streams in the mountainous areas of the basin are generally small. Relative to the intense localized convective rainstorms of the basins and plains areas, mountain snow accumulations are less variable in aerial extent and between years. The coefficients of variation in annual discharge at sites 1-4, 9, 16, and 18 (table 1) are about 0.2. Coefficients of variation are slightly larger (0.3 to 0.4) at sites on the northern and eastern flanks of the Bighorn Mountains (sites 7, 24, 25, 37, and 38).

Most streams originating in the basins or plains areas of the YRB are ephemeral, flowing only as a result of local snowmelt or intense rainstorms (Wahl, 1970; Omang, 1992). Intense localized convective rainstorms can produce most of the total flow for any given year in these watersheds. The distribution and occurrence of these events vary between years (Lowham, 1988, p. 18). Because of the localized extent and annual variability of these storms, the resulting flows in any given watershed are variable between years. Annual flows of streams originating in the basin or plains areas often consist of multiple peaks: a lowland snowmelt peak of moderate duration occurring late winter/early spring and several rainstorm peaks of short duration occurring late spring through late summer (fig. 13 B).

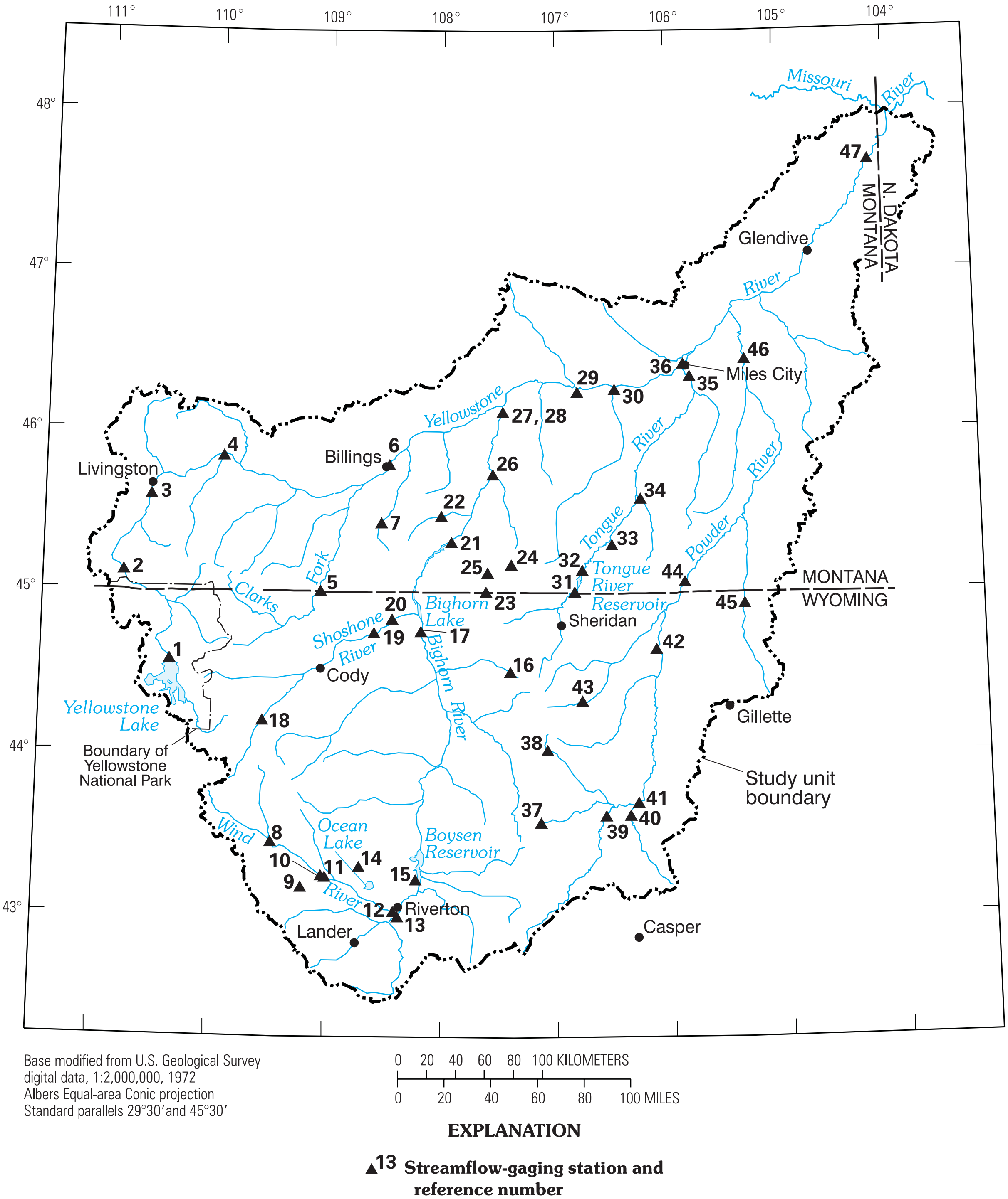


Figure 12. Hydrography and selected streamflow-gaging stations, Yellowstone River Basin, Montana, North Dakota, and Wyoming.

Table 1. *Basin characteristics and annual streamflow statistics at selected sites, Yellowstone River Basin*

[Number of years in analyses refers to complete years used in computation of annual streamflow statistics; km^2, square kilometer; m^3/sec, cubic meter per second; ft^3/sec, cubic feet per second; Yellowstone River mainstem stations shaded; YNP, Yellowstone National Park; MT, Montana, WY, Wyoming; NR, not relevant]

Reference number (fig. 12)	Station number	Streamflow-gaging station	Elevation (m above sea level)	Drainage area (km^2)	Annual streamflow: Mean annual (m^3/sec)	Annual streamflow: Mean annual (ft^3/sec)	Annual streamflow: Coefficient of variation	Annual streamflow: Number of years in analyses
1	06186500	Yellowstone River at Yellowstone Lake Outlet, YNP	2,356	2,606	37.6	1,328	0.23	67
2	06191500	Yellowstone River at Corwin Springs, MT	1,548	6,794	87.9	3,104	.21	90
3	06192500	Yellowstone River near Livingston, MT	1,385	9,197	105	3,731	.19	71
4	06200000	Boulder River at Big Timber, MT	1,237	1,350	16.3	575	.24	47
5	06207500	Clarks Fork Yellowstone River near Belfry, MT	1,215	2,989	26.5	934	.22	75
6	06214500	Yellowstone River at Billings, MT	939	30,549	198	6,988	.23	68
7	06216000	Pryor Creek at Pryor, MT	1,221	303	.973	34.4	.35	29
8	06220500	East Fork Wind River near Dubois, WY	1,960	1,110	6.94	245	.30	28
9	06224000	Bull Lake Creek above Bull Lake, WY	1,790	484	8.29	293	.20	42
10	06225000	Bull Lake Creek near Lenore, WY	1,723	552	7.76	274	.25	75
11	06225500	Wind River near Crowheart, WY	1,718	4,898	34.0	1,201	.21	51
12	06228000	Wind River at Riverton, WY	1,494	5,980	23.1	815	.44	81
13	06235500	Little Wind River near Riverton, WY	1,494	4,931	16.3	575	.19	55
14	06244500	Fivemile Creek above Wyoming Canal, near Pavillion, WY	1,680	306	.0937	3.30	1.57	34
15	06253000	Fivemile Creek near Shoshoni, WY	1,450	1,080	4.50	159	.21	44
16	06278300	Shell Creek above Shell Reservoir, WY	2,760	59.8	.988	34.9	.21	40
17	06279500	Bighorn River at Kane, WY	1,120	40,831	62.9	2,222	.27	67
18	06280300	South Fork Shoshone River near Valley, WY	1,890	769	11.6	411	.22	39
19	06284500	Bitter Creek near Garland, WY	1,240	208	4.05	143	.11	25
20	06285100	Shoshone River near Lovell, WY	1,170	6,090	25.6	903	.34	30
21	06287000	Bighorn River near St. Xavier, MT	963	50,938	98.8	3,490	.24	62
22	06288200	Beauvais Creek near St. Xavier, MT	1,020	259	.668	23.6	.51	10
23	06289000	Little Bighorn River at State Line, near Wyola, MT	1,330	500	4.25	150	.24	56
24	06290500	Little Bighorn River below Pass Creek, near Wyola, MT	1,100	1,110	5.89	208	.32	55
25	06291500	Lodge Grass Creek above Willow Creek Diversion, near Wyola, MT	1,270	209	1.37	48.4	.32	49
26	06294000	Little Bighorn River near Hardin, MT	879	3,351	8.23	290	.44	43
27	06294500	Bighorn River above Tullock Creek, near Bighorn, MT	823	58,052	108	3,810	.25	51

Table 1. *Basin characteristics and annual streamflow statistics at selected sites, Yellowstone River Basin (Continued)*

Reference number (fig. 12)	Station number	Streamflow-gaging station	Elevation (m above sea level)	Drainage area (km^2)	Annual streamflow: Mean annual (m^3/sec)	Mean annual (ft^3/sec)	Coefficient of variation	Number of years in analyses
28	06294700	Bighorn River at Bighorn, MT	NR	59,272	[a]	[a]	NR	NR
29	06294995	Armells Creek near Forsyth, MT	780	958	.163	5.75	1.04	18
30	06296003	Rosebud Creek at mouth, near Rosebud, MT	756	3,372	.892	31.5	.98	22
31	06306300	Tongue River at State Line, near Decker, MT	1,045	3,825	13.1	462	.33	36
32	06307500	Tongue River at Tongue River Dam, near Decker, MT	1,019	4,580	12.6	446	.33	57
33	06307600	Hanging Women Creek near Birney, MT	960	1,220	.0997	3.52	.97	21
34	06307740	Otter Creek at Ashland, MT	889	1,830	.134	4.72	.91	21
35	06308500	Tongue River at Miles City, MT	719	13,980	11.9	421	.44	53
36	06309000	Yellowstone River at Miles City, MT	711	124,980	324	11,440	.23	69
37	06309200	Middle Fork Powder River near Barnum, WY	2,200	117	.849	30.0	.35	35
38	06311000	North Fork Powder River near Hazelton, WY	2,490	63.5	.423	14.9	.30	50
39	06313000	South Fork Powder River near Kaycee, WY	1,400	2,980[b]	1.03	36.5	.55	23
40	06313400	Salt Creek near Sussex, WY	1,370	1,990	1.28	45.1	1.21	16
41	06313500	Powder River at Sussex, WY	1,331	8,000	5.76	204	.48	25
42	06317000	Powder River at Arvada, WY	1,100	15,700	7.85	277	.46	65
43	06318500	Clear Creek near Buffalo, WY	1,580	311	1.75	61.9	.39	64
44	06324500	Powder River at Moorhead, MT	1,016	20,950	12.8	452	.42	65
45	06324970	Little Powder River above Dry Creek, near Weston, WY	1,040	3,199	.622	22.0	1.22	24
46	06326500	Powder River near Locate, MT	727	34,160	16.6	586	.51	58
47	06329500	Yellowstone River near Sidney, MT	573	178,980	361	12,750	.27	84

[a]Flow equivalent to USGS 06294500 (site 27).

[b]Estimated.

Table 2. *Mean annual runoff for major tributaries and the mainstem as measured at selected sites, Yellowstone River Basin* (Modified from Shields and others, 1997)

[km^2, square kilometer; m^3/sec, cubic meter per second; ft^3/s, cubic feet per second; cm, centimeter; in., inches]

Site			Drainage area (km^2)[b]	Mean annual flow (m^3/sec and (ft^3/s))	Mean annual runoff (cm and (in.))	Period represented
Reference number (fig. 12)	Station number[a]	Tributary and/or part of mainstem represented by station				
6	06214500	Yellowstone headwaters/Upper Yellowstone/ Clarks Fork Yellowstone River	30,549	198 (6,988)	20.4 (8.04)	1929-96
27	06294500	Wind/Bighorn River	58,052	111 (3,910)	6.03 (2.37)	1967-96[c]
35	06308500	Tongue River	13,980	11.9 (421)	2.68 (1.06)	1938-96
46	06326500	Powder River	34,160	16.6 (586)	1.51 (.60)	1939-96
47	06329500	Yellowstone River Basin	178,980	359 (12,660)	6.33 (2.49)	1967-96[c]

[a]For tributaries, station represents site closest to the tributary mouth.
[b]Drainage area at site is less than total area of river basin.
[c]Period after completion of Yellowtail Dam (Bighorn Lake).

Several streams that originate in the basins and plains areas of the YRB are characterized by large variability in annual streamflow. Coefficients of variation in annual mean discharge at representative sites are about 1.0 or larger (sites 29, 30, 33, 34, 40, and 45) (table 1).

Larger streams with headwaters in mountainous areas of the YRB that flow across the basins and plains exhibit a combination of annual streamflow characteristics of mountain, basin, and plains streams. Annual flows consist of a lowland snowmelt peak during late winter/early spring followed by a peak from the mountain snowmelt during late spring/early summer with several short to moderate duration rainstorm peaks superimposed on the snowmelt peak and throughout the remainder of the summer (figs. 13 C and G). Coefficients of variation are moderate at representative sites on the Tongue, Powder, and Yellowstone Rivers, ranging from more than 0.2 to about 0.5 (sites 35, 36, 41, 42, 44, 46, and 47) (table 1).

Flows in some streams in the YRB are affected by various flow modifications. In some watersheds where irrigated agriculture is a major land use, most of the streamflow results from agricultural return flows and sustained base flows. Formerly intermittent or periodically ephemeral streams often flow perennially upon the development of irrigation (Colby and others, 1956; Plafcan and others, 1993). Annual flows generally are uniform throughout the irrigation season, with a gradual decrease to a sustained base flow following the end of the growing season (fig. 13 D). Relative to the event-based annual flows in undeveloped ephemeral drainages, these flows are generally less variable between years. Variabilities in annual flows for two representative watersheds in the basin are very low; coefficient of variation at site 15 is 0.21 and at 19 is 0.11 (table 1). Streamflow characteristics of perennial streams below major diversions or reservoirs sometimes exhibit large variations during high flows (fig. 13E). Coefficients of variations at representative sites in the Wind/Bighorn River Basins are moderate (sites 12 and 20) (table 1).

Flow Duration

Streamflow duration is the time over which a given discharge is recorded at a site. For all discharges at a site during the period of record or interest, flow durations can be summarized graphically as a curve derived by plotting each discharge with the cumulative exceedance probability (in percent) for that discharge.

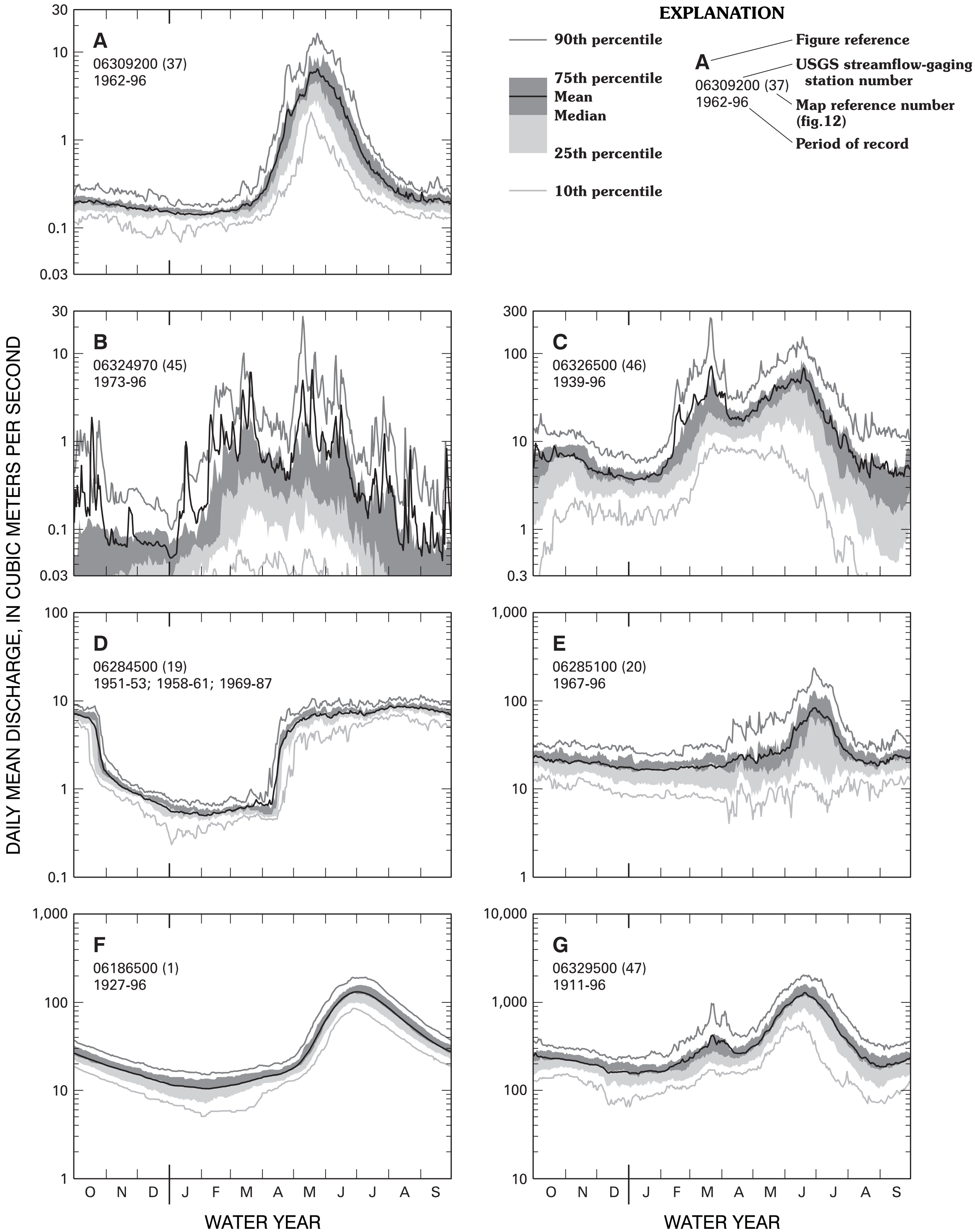


Figure 13. Statistical summary of daily mean streamflow for period of record at selected streamflow-gaging stations, Yellowstone River Basin.

The resulting flow-duration curve shows the percentage of time during which a range of flows were equaled or exceeded during the period of interest without consideration for the chronology of the individual flows. Thus, the curve is a graphical representation of the variability of streamflow at a site over an entire period of interest. The shape of the flow-duration curve is a function of the basin hydrological and physical characteristics. If flow-duration curves are based on representative data, the curves are useful for predicting flow distributions for water-quality assessments (Searcy, 1959).

Most of the flow in perennial streams that originate in the mountainous areas of the YRB is from snowmelt (see previous section on *Annual Streamflow*). Site 9 (fig. 12) is representative of streams originating in the mountainous areas of the basin. The flow-duration curve for site 9 (fig. 14 A) is generally flat for high and low flows, illustrating the small variability in flows typical of perennial streams. The flatness of the curve for both small and large exceedances is typical of a perennial stream with consistent high flows and sustained low flows from snowmelt.

Ephemeral streams that originate in the basins or plains areas of the YRB flow only as a result of snowmelt or rainstorms. As described previously (see *Annual Streamflow* section), these snowmelt and rainstorm events vary greatly in intensity, duration, frequency, and extent. Because flows in the basins and plains areas are in response to these discrete events, the variability in streamflows depends on the variability of the events. Similarly, periods of no flow are common; low or base flows from surface- or ground-water storage, if present, generally do not persist throughout the year nor throughout the stream reaches (Omang, 1983; Parrett, 1983; Rankl and Armentrout, 1986). Site 45 (fig. 12) is representative of streams, with few effects from flow modifications, that originate in the basin and plains areas of the YRB. The flow-duration curve for site 45 (fig. 14 C) is generally steep throughout most of the range of flows, illustrating the large variability in flows typical of ephemeral streams. The steepness of the curve for large exceedances also is typical of ephemeral streams, illustrating the lack of sustained low or base flows.

Streams that originate in the mountains and flow across the basins and plains areas generally are perennial. Larger drainage areas, snowmelt runoff, and ground-water sources minimize variability in high and low flows (Omang, 1986). The flatness of flow-duration curves for sites 6, 36, and 47 (fig. 14 G) on the mainstem Yellowstone River illustrates the low variabilities in flows in these types of streams. Some streams, however, lose flow in the plains areas of the basin, resulting in intermittent flow some years. Ringen and Daddow (1990) attributed net losses in streamflow along the Powder River during 1978-80 at sites 42 and 44 (fig. 12) to seepage and evapotranspiration. Such losses result in more variability in base flows, a condition illustrated by the moderately steep flow-duration curve for site 46 on the Powder River (fig. 14 D).

Flow modifications have affected flow durations of some streams in the YRB. In some watersheds, land-use practices augment natural flows to sites downstream. Inflows from irrigation drainage below site 14 have resulted in lower streamflow variability and sustained base flows at site 15 (fig. 12). The resulting flow-duration curve is similar to that of a perennial stream (fig. 14 B). Ground water is pumped and discharged as surface water during the production of oil and gas in some watersheds. Such produced water is discharged upstream from site 40, resulting in perennial flow in what was once an ephemeral stream (Lindner-Lunsford and others, 1992). The resulting flow-duration curve is flat for large exceedances, illustrating the sustained base-flows (fig. 14 C, site 40). Flows are completely regulated by reservoirs in some watersheds in the YRB. Variations in flow are low at site 21 (fig. 12) downstream of Bighorn Lake (Yellowtail Dam). The flow-duration curves for the periods after the completion of Boysen Reservoir (1952-61 and 1967-96) are flat throughout the range of all flows, illustrating that the regulated flows are sustained for most exceedances (fig. 14 E, site 21).

The composite effects of flow modifications in the YRB decrease streamflow variability. At the mouth of the basin, the decrease in streamflow variability over time is illustrated in flow-duration curves for site 47 (fig. 14 F). The curves represent periods between completion of major reservoirs in the basin. The cumulative effect of sustained regulated flows from reservoir releases results in the flattening of the flow-duration curve, indicating less variability in streamflows. In addition to flow modifications, climate changes influence the overall variability in streamflows in the basin. The period 1952-61 represents the time after which operation of Boysen Reservoir began and before which construction of Yellowtail Dam (Bighorn Lake) was completed (fig. 14 E and F). Overlapping this period, the drought of 1948-62 had severe effects on most of Wyoming and Montana (see following section).

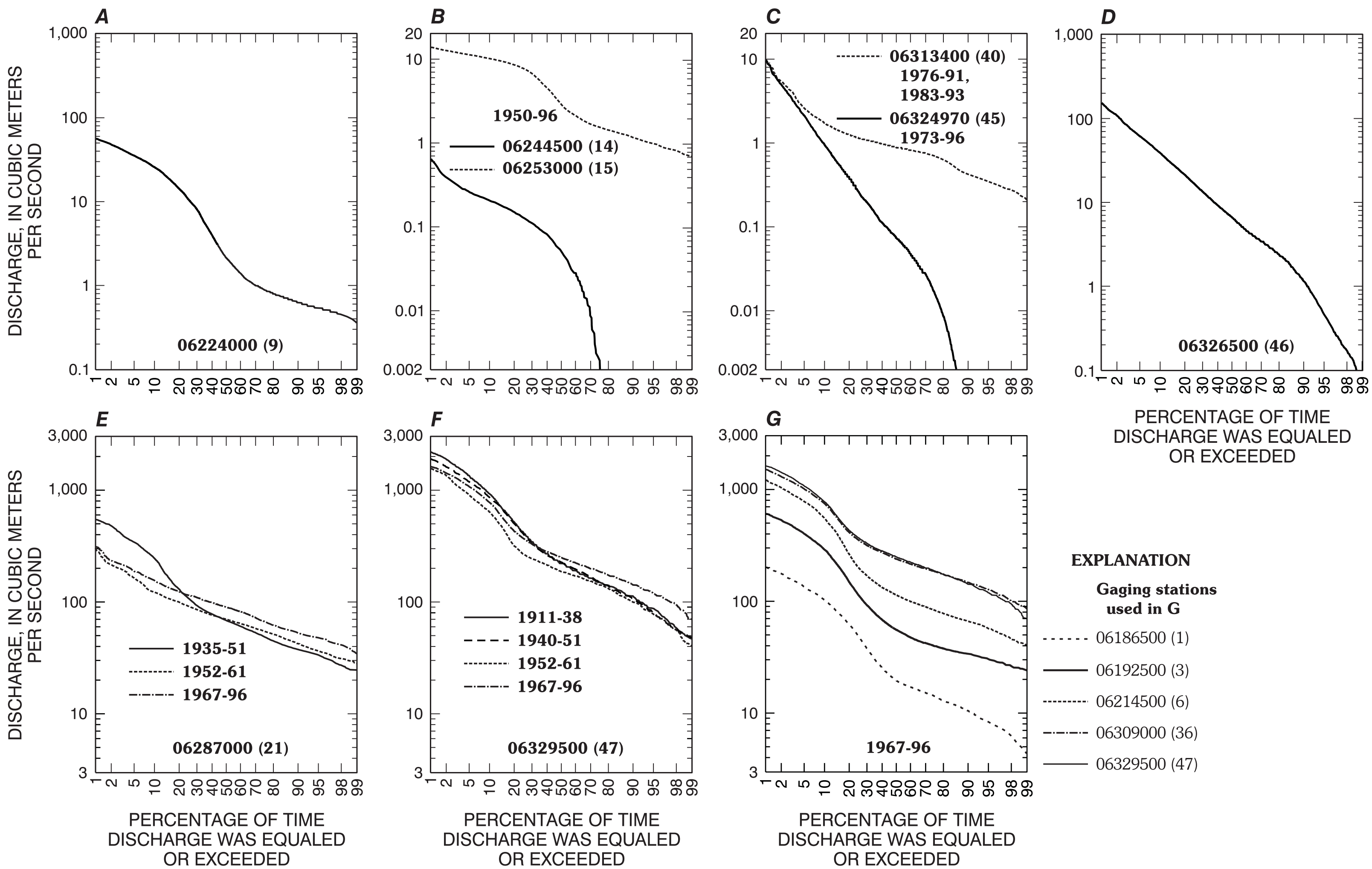


Figure 14. Streamflow duration curves for selected periods at selected streamflow-gaging stations, Yellowstone River Basin (streamflow-gaging station number and map reference number (in parentheses) are shown on figure 12 and listed in table 1).

Floods and Droughts

Diverse geographic features and variable moisture systems combine to cause severe floods and droughts in the YRB (Druse, 1991; Merritt and others, 1991). Floods and droughts are extreme hydrologic events that can degrade ambient surface-water quality. The highest constituent loads from nonpoint sources, such as overland flow, occur during flooding (Novotny and Olem, 1994). Floodwaters can scour gravels and deposit sediment, processes that are detrimental to spawning beds for some fish species (Merritt and others, 1991). Decreased flows during drought periods lessen the diluting effect of streams on inflows (including surface and ground water), potentially resulting in increased concentrations of dissolved solids. Lower dissolved-oxygen levels and higher stream temperatures also may occur during extended periods of low flows, adversely affecting aquatic life (Matthai, 1979).

Floods

Flooding in the YRB can occur as a result of snowmelt, widespread rainfall, or intense thunderstorms. In mountainous areas of the basin, most flooding occurs during spring and early summer from rapid snowmelt. Flooding in the basins and plains areas occurs during winter and early spring from lowland snowmelt, during spring from large regional rainstorms, and during summer and fall from intense localized thunderstorms. High antecedent soil moisture, frozen ground, and rainfall on melting snowpacks contribute to the most severe floods (Craig and Rankl, 1978; Lowry and others, 1986; Lowham, 1988; Druse, 1991; Omang, 1992; Holnbeck and Parrett, 1996).

Flooding occurred during 1923 in parts of the YRB during July 23-25 and again during September 27-30 as a result of widespread thunderstorms and rainfall. Referred to by long-term residents as “the big floods of 1923,” these were the most severe floods since 1880 and were during the period 1918-27 in which more large floods occurred in Wyoming than any other decade (Cooley, 1990). Peak flow recurrence intervals exceeded 100 years at several USGS stations in the Wind, Bighorn, and Powder River Basins (Druse, 1991). The 1923 peak discharge at site 42 (Powder River at Arvada, Wyoming; fig. 12) of 2,830 m^3/sec (Smalley and others, 1997) is twice the next largest peak of record (period of record 1919-96).

Severe flooding occurred during May 1978 in southeastern and south-central Montana and northeastern Wyoming (Merritt and others, 1991). Watersheds affected in the basin included the Yellowstone River from near Billings, Montana, to Miles City, Montana; the Bighorn, Tongue, and Powder Rivers; and many smaller tributary watersheds (Parrett and others, 1984). Widespread rain on saturated soils combined with bankfull snowmelt runoff conditions in most streams to cause the flooding. Flood recurrence intervals exceeded 50 years for most of the affected area (Merritt and others, 1991). Sediment transport is often very high during floods. Record maximum daily suspended-sediment loads at four sites were measured on the Powder River (table 3). Other major floods occurred in the YRB during 1918, 1962, 1963, and 1981 (Druse, 1991; Merritt and others, 1991).

Droughts

Severe droughts of several-years duration have occurred in the YRB. Droughts with recurrence intervals greater than 25 years occurred during the periods 1929-42 and 1948-62 over most of Wyoming and Montana (Druse, 1991; Merritt and others, 1991), including nearly all of the YRB. Such regional drought conditions are common in the upper parts of the Missouri River Basin (Matthai, 1979). Droughts with recurrence intervals of 10 to 25 years occurred in the YRB between 1976 and 1982. Recent data for representative streamflow-gaging stations in the basin used in previous drought analyses by Druse (1991) and Merritt and others (1991) indicate lower than normal flows from about 1987 to about 1994 (table 4).

The drought of 1977 affected most of the United States west of the Mississippi River (Matthai, 1979, fig. 2). In the YRB, the 1977 drought was part of the 1976-82 drought period; the most severely affected areas were the upper parts of the Wind and Yellowstone River watersheds (Druse, 1991; Merritt and others, 1991). Decreased streamflows during droughts can result in higher dissolved-solids concentrations. Median concentrations of total dissolved solids in samples collected during September through the following February of each year (that is, the period of year during which flows are lower) were significantly higher (Wilcoxon rank-sum test; $p < 0.05$) during the drought period 1976-82 than during non-drought years at sites 3 and 6 on the upper Yellowstone River (table 5). Dissolved-solids concentrations were higher during the

Table 3. *Maximum daily suspended-sediment discharge, flood of May 1978, Powder River, Wyoming and Montana*

(From Parrett and others, 1984)

[m^3/s, cubic meters per second, ft^3/s, cubic feet per second]

Reference number (fig. 12)	Powder River streamflow-gaging station		Date	Maximum flood discharge (m^3/s and (ft^3/s))	Suspended-sediment discharge (megagrams)
	Number	Location			
42	06317000	at Arvada, Wyoming	May 20, 1978	[a]920 (32,500)	2,550,000
44	06324500	at Moorhead, Montana	May 20, 1978	935 (33,000)	2,020,000
[b]	06324710	at Broadus, Montana	May 21, 1978	850 (30,000)	1,420,000
46	06326500	near Locate, Montana	[c]May 22, 1978	776 (27,400)	670,000

[a]Approximate measurement.
[b]Location not shown on figure 12.
[c]Maximum flood discharge occurred on May 23.

Table 4. *Annual departure from mean annual discharge at selected streamflow-gaging stations, Yellowstone River Basin, water years 1987-96*

(Modified from U.S. Geological Survey, 1997c)

[06191500 (2), station number and (reference number, fig. 12); --, no data]

Water year	Annual departure from mean annual discharge, in percent					
	06191500 (2)	06214500 (6)	06225500 (11)	06317000 (42)	06318500 (43)	06324500 (44)
1987	-32.5	-30.3	-11.4	21.7	-2.6	7.2
1988	-36.4	-36.4	-31.2	-43.8	-33.5	-40.2
1989	-9.8	-11.1	-22.1	-53.5	-22.5	-64.7
1990	-3.6	-10.3	-14.2	-31.6	6.3	-22.0
1991	3.0	4.2	10.2	-12.9	31.9	8.4
1992	-11.1	-9.5	-32.9	-39.5	31.7	-23.0
1993	11.9	9.0	-16.3	36.3	--	29.1
1994	-22.6	-30.3	-34.4	-34.1	--	-31.2
1995	6.9	12.6	4.7	130	--	75.9
1996	45.4	38.6	12.5	-8.8	--	2.1

1976-82 drought than during non-drought periods at site 12 on the Wind River; however, the difference was not significant (table 5). Site 12 might not be representative of drought conditions in the upper parts of the Wind River watershed because of flow modifications upstream of the site.

Water-Quality Characteristics

Concentrations of suspended sediments and dissolved solids in streams are indicators of water quality that are useful for characterizing the overall water-quality conditions of the YRB. Suspended-sediment and dissolved-solids concentrations are smaller in mountain streams overlying older rocks than in streams crossing the younger rocks of the basins and plains areas. Human activities that disturb the land contribute to suspended sediment and dissolved solids in surface water. Concentrations of suspended sediment and dissolved solids in streams in the basin vary with streamflow and season.

Table 5. *Statistics for total dissolved-solids concentration at selected sites, September-February, during non-drought and drought periods, upper Wind and Yellowstone Rivers, 1969-94*

[n, number of analyses; mg/L, milligrams per liter; Y, yes; N, no]

Reference number (fig. 12)	Station number	Non-drought periods		1976-82 drought		
		n	Median concentration (mg/L)	n	Median concentration (mg/L)	Significance (p-value)[a]
3	06192500	60	172	33	183	Y (p=0.0239)
6	06214500	89	272	38	282	Y (p=0.0363)
12	06228000	93	277	37	287	N (p=0.1752)

[a]Wilcoxon rank-sum test for significance; one-sided p-value. Higher concentrations of total dissolved solids during the 1976-82 drought are significant at the 95-percent confidence level if $p < 0.05$.

Suspended Sediment

The concentration of sediment in suspension in a stream is an indicator of water quality. Suspended-sediment data are useful in describing general basin water-quality conditions. Suspended sediment includes fragments of rock and soil that are transported in suspension by streams. Overland flow and channel scour are important erosional sources of suspended sediment in watersheds with little development; mass wasting contributes substantially to sediment loads in some systems (Colby and others, 1956). While much of the suspended sediment in streams is the result of natural factors, some human activities also contribute to sediment loads. Large suspended-sediment concentrations in streams tend to occur in range and agricultural land-use areas because of the high erodibility of soils in these areas (Smith and others, 1993).

Concentrations of suspended sediment in the YRB generally are lower in mountain streams than in streams draining the basins and plains areas. Most of the fluvial sediment in the basin is derived from the basins and plains areas (Hembree and others, 1952; Colby and others, 1956). About 30 percent of the annual sediment load at site 47 (fig. 12) is from the Powder River Basin, in spite of the fact it accounts for less than 5 percent of the annual streamflow (Knapton and Bahls, 1993). Statistical summaries of data from selected sites on the Wind and Powder Rivers illustrate the large concentrations of suspended sediment in the basins and plains streams (fig. 15). Suspended-sediment concentrations increase downstream in the Tongue River Basin (Litke and Knapton, 1983). A decrease in suspended-sediment concentrations between sites 42 and 46 (fig. 12) on the Powder River might be attributed to significant sediment deposition through this reach (fig. 15; also, Martinson and Meade, 1983; and, Ringen, 1986).

Suspended-sediment concentrations in streams in the YRB generally are lower in watersheds where older rocks are exposed, such as resistant Precambrian and Paleozoic rocks. Concentrations of suspended sediment generally are larger in streams in contact with less resistant rocks of Mesozoic age and younger. Important sources of suspended sediment in the basins and plains watersheds include actively eroding gullies as well as erosion of the channel alluvium (Hembree and others, 1952; Colby and others, 1956).

Fluvial sediment is contributed by land-use activities in some watersheds in the YRB. Irrigation practices in the Clarks Fork Yellowstone River Basin, as well as natural factors, contribute a substantial part of the suspended sediment measured at site 6 (Knapton and Bahls, 1993). Prior to the completion of Boysen Reservoir, over half of the suspended-sediment load in the Bighorn River upstream of site 17 was contributed by Fivemile Creek (fig. 12, sites 14 and 15; see also *Flow Duration* section in this report). Colby and others (1956) determined 87 percent of the sediment load in Fivemile Creek originated within the irrigated area.

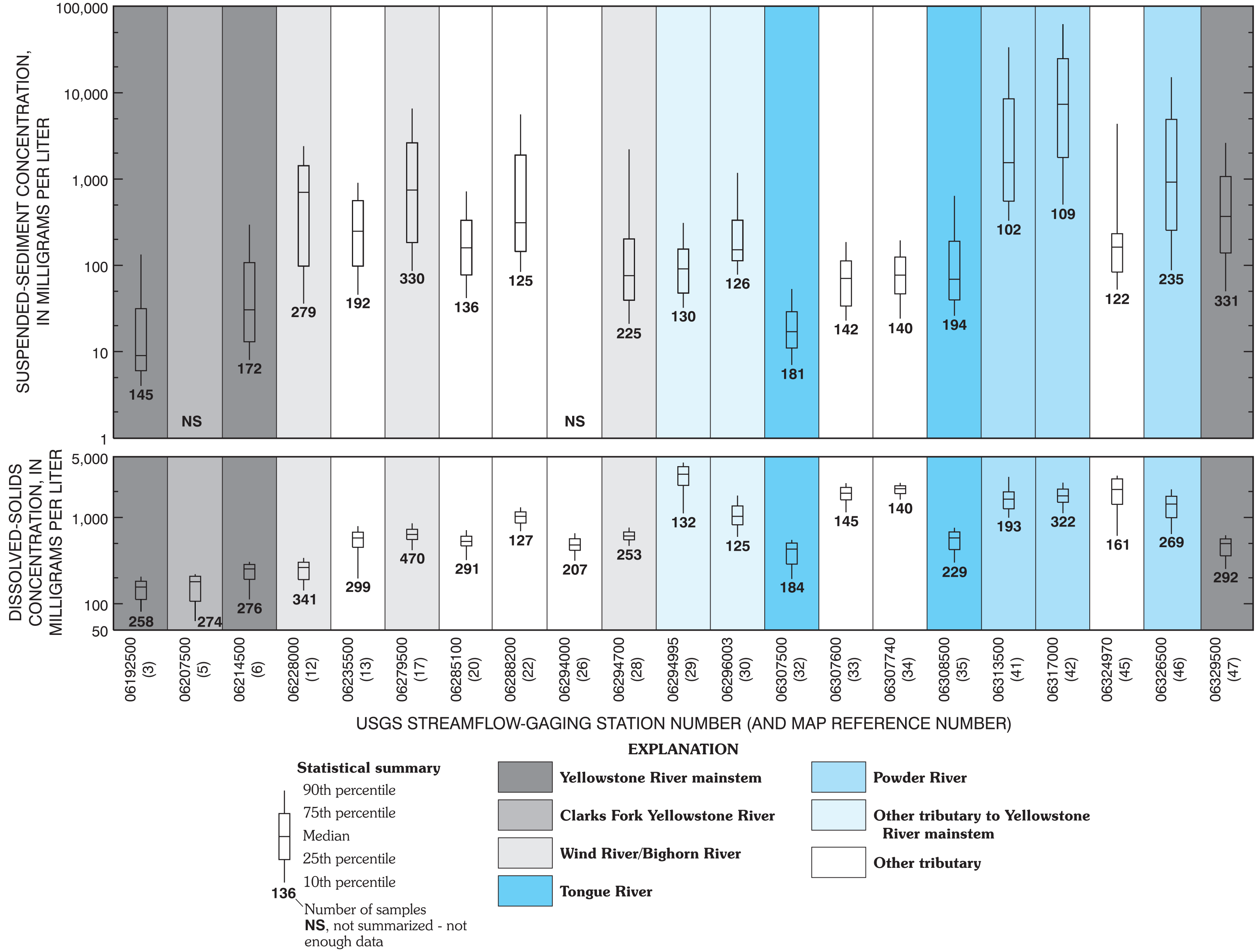


Figure 15. Statistical summary diagrams of suspended-sediment and dissolved-solids concentrations at selected streamflow-gaging stations, Yellowstone River Basin (stations are in downstream order from left).

Suspended-sediment concentrations in alluvial streams with little or no flow modifications generally increase with increasing streamflow (Leopold and Maddock, 1953). In the YRB, the positive correlation between suspended-sediment concentrations and discharge is strong because of relatively high suspended-sediment concentrations and large seasonal and annual variability in streamflows. The largest concentrations in basins and plains streams usually occur during periods of direct runoff when erosion from overland flow and channel scour contribute the most sediment (Lambing, 1986). The correlation of suspended-sediment concentrations with discharge is generally poor in watersheds where natural flows are altered or where sources of sediment are limited.

Suspended-sediment concentration generally correlates well with discharge at selected sites in the YRB where suspended-sediment concentrations are relatively high. Suspended-sediment concentrations are the highest in the Powder River Basin; correlation coefficients range from about 0.7 to nearly 0.8 at selected sites (table 6; sites 41, 45, and 46). The good correlation between suspended-sediment concentration and discharge at site 12 (Spearman rank correlation coefficient = 0.84) might be more a function of sediment-flushing flows from a diversion dam upstream from the site rather than one of natural streamflow and suspended-sediment conditions.

Correlation of suspended-sediment concentration with discharge generally diminishes at selected sites in watersheds with streamflow modifications. Sites 17, 20, 28, and 35 are downstream from major reservoirs and irrigation diversions and returns. Suspended-sediment concentrations do not correlate well with discharge at site 28, where more than 90 percent of the mean annual flow is controlled by releases from Bighorn Lake (Yellowtail Dam). Decreased stream velocities at reservoir inlets result in the deposition of suspended sediment; consequently, suspended-sediment concentrations are limited in flows from reservoir outlets.

Dissolved Solids

Dissolved-solids concentrations in surface waters are composite water-quality indicators that can be used to characterize the general water quality of a watershed. Total dissolved solids represents the sum of all dissolved constituents in a water sample. For watersheds without substantial development, the major dissolved constituents detected in streams result from the dissolution of minerals in soil and rock (Hem, 1985; Drever, 1988). Dissolved-solids concentrations are generally lower in forested watersheds and areas of higher precipitation; concentrations are generally higher in rangeland watersheds and regions of lower precipitation. Human activities that disturb the land, such as agriculture, mining, and other development, can increase dissolved solids in surface waters by exposing more minerals for dissolution (Smith and others, 1993). Concentrations of dissolved solids generally are inversely related to streamflow (Hem, 1985); thus, dissolved-solids concentrations vary with seasonal variations in streamflow.

Table 6. *Correlation of suspended-sediment and dissolved-solids concentration with instantaneous discharge at selected sites, Yellowstone River Basin*

[n, number of sample/discharge pairs; --, too few sample/discharge pairs: correlation not computed]

		Suspended-sediment concentration		Dissolved-solids concentration	
Reference number (fig. 12)	Station number	n	Spearman rank correlation coefficient[a]	n	Spearman rank correlation coefficient[a]
3	06192500	141	0.62	147	-0.97
5	06207500	--	--	124	-.86
6	06214500	170	.57	142	-.86
12	06228000	163	.84	131	-.57
13	06235500	92	.66	101	-.72
17	06279500	282	.56	137	-.81
20	06285100	114	.45	114	-.81
28	06294700	163	.28	149	-.26
35	06308500	156	.66	137	-.45
41	06313500	95	.79	170	-.58
42	06317000	--	--	176	-.69
45	06324970	119	.71	161	-.50
46	06326500	196	.78	145	-.69
47	06329500	296	.65	186	-.53

[a]See Helsel and Hirsch (1992) for description of Spearman rank correlation coefficient.

Concentrations of dissolved-solids in the YRB generally are lower in streams in mountainous areas than in those originating in the basins or plains areas (Knapton, 1983; Lambing, 1986; Larson, 1986; Peterson, 1987). Dissolved solids generally increase in streams flowing across the basins and plains areas of the YRB (Lowry, Smalley, and others, 1993; Peterson, 1993; Susong and others, 1993; Plafcan and Ogle, 1994). Statistical summaries of data from selected sites on streams in the Powder River Basin and tributaries to the Yellowstone and Tongue Rivers illustrate dissolved-solids concentrations are relatively high in streams originating in the plains areas of the YRB (fig. 15, sites 29, 30, 33, 34, and 45). Dissolved-solids increase downstream at representative sites on the Wind/Bighorn and Tongue Rivers, as well as on the mainstem Yellowstone River, which originate in the mountains and flow across the basins and plains areas (fig. 15, sites 12, 17, and 28; 32 and 35; and 3, 6, and 47, respectively).

Dissolved-solids concentrations in streams in the YRB are generally lower in watersheds overlying most older and some younger rocks. Dissolved solids are low in watersheds where Precambrian igneous and metamorphic rocks or more resistant Paleozoic sedimentary rocks predominate. Watersheds mostly underlain by Tertiary volcanic rocks also are low in dissolved solids. Concentrations of dissolved solids are generally higher in streams in contact with less resistant younger rocks. Dissolved solids are relatively high in watersheds draining mostly Mesozoic sandstones, siltstones, and shales, in particular, the Cody Shale and other Cretaceous marine shales (Hembree and others, 1952; Colby and others, 1956). Thermal springs along the upper Yellowstone and Bighorn Rivers are other geologic sources of dissolved solids (Knapton and Bahls, 1993; Peterson, 1993).

Various land-use practices contribute to dissolved solids in streams in some watersheds in the YRB. Irrigation practices contribute to dissolved solids in streams in the Clarks Fork Yellowstone, Wind/Bighorn, and Powder River Basins (Knapton and Bahls, 1993; Cary, 1991; Peterson and others, 1991; Lowry, Smalley, and others, 1993; Larson, 1986). Oil and gas development contributes to dissolved solids in the Wind/Bighorn (Lambing, 1986) and Powder River Basins. The Salt Creek watershed contributes approximately 25 to 30 percent of the dissolved solids at site 41 (fig. 12) on the Powder River; most of this load is from saline oil-production water (Lindner-Lunsford and other, 1992; Peterson, 1993).

Concentrations of dissolved solids generally are higher at lower discharges in most streams in the YRB. Ground water and other inflows contribute a substantial part of the lower flows in many streams of the basin and plains areas. Concentrations of dissolved solids in ground water, irrigation drainage, and wastewater discharge generally are higher than those in the receiving streams. Thus, the concentration of dissolved solids in streams increases during lower flows. Conversely, dissolved-solids concentrations are lower at higher discharges. Higher flows generally are the result of runoff from snowmelt or rainstorms, sources with very low concentrations of dissolved solids. Other inflows are diluted by the runoff, thereby decreasing the concentration of dissolved solids (Colby and others, 1956; Knapton, 1983; Lambing, 1986; Larson, 1986).

Correlation of dissolved-solids concentration with instantaneous discharge ranges from excellent to poor at selected sites in the YRB. Concentrations of dissolved solids correlate well with discharges at sites in the Clarks Fork Yellowstone and Wind/Bighorn Basins and on the upper mainstem Yellowstone River (table 6, sites 3, 5, 6, 13, 17, and 20). Dissolved-solids concentration does not correlate as well with discharge at site 12 (Spearman rank correlation coefficient = -0.57); upstream releases of very dilute reservoir waters contribute to a wide range of dissolved concentrations at lower flows (Colby and others, 1956, p. 123). Dissolved-solids concentrations do not correlate as well with discharges at selected sites in the Tongue and Powder River Basins (sites 35 and 45). Dissolved-solids concentrations increase initially during event-based flows in streams in the basins and plains areas from washoff of naturally occurring salts and larger ambient concentrations in tributary streams (Larson, 1986; Lindner-Lunsford and others, 1992; and, Lowry and others, 1993). Dissolved-solids concentrations do not correlate well with discharges at site 28 (Spearman rank correlation coefficient = -0.26) downstream from Bighorn Lake. Reservoirs function as holding and mixing basins in watersheds, affecting the quality of surface waters downstream (Hem, 1985).

Concentrations of dissolved solids vary by season at some sites in the YRB. Because dissolved-solids concentrations generally are related to streamflows and much of the variation in streamflows is seasonal, site-specific variation in dissolved-solids concentrations in the basin also is seasonal. Thus, dissolved-solids concentrations generally are higher during the fall and winter and lower during the spring and summer.

Concentrations of dissolved solids are significantly higher (table 7) during the winter (January through March) than during any other season at site 26 (fig. 12). Dissolved-solids concentrations are lowest during the spring; however, the difference is only significant (table 7) when compared to the fall and winter months.

Table 7. *Seasonal variability in total dissolved-solids concentration in stream samples collected at site 26, Little Bighorn River near Hardin, Montana, 1970-96*

[Site 26 shown in fig. 12; mg/L, milligrams per liter; Fall, October-December; Winter, January-March; Spring, April-June; Summer, July-September; Y, significant, N, not significant]

Season	Significance (p-value)[a] Summer	Significance (p-value)[a] Spring	Significance (p-value)[a] Winter	Number of samples	Sample median (mg/L)
Fall	Y (p<0.0001)	Y (p=0.0350)	Y (p=0.0062)	45	492
Winter	Y (p<0.0001)	Y (p=0.0014)	--	47	556
Spring	N (p=0.4537)	--		62	411
Summer	--			50	438

[a]Wilcoxon rank-sum test for significance; two-sided p-value (Helsel and Hirsch, 1992). Difference in concentration between any two seasons is significant at the 95-percent confidence level if $p < 0.05$.

Stream Ecology

Ecologists are concerned with interrelations between biological communities and their habitat. A variety of biological, chemical, and physical factors control the abundance, distribution, and productivity of aquatic organisms (Gordon and others, 1992, p. 17). Competition for preferred habitat, predation, water chemistry, nutrient inputs, the presence of waterfalls or dams, and streamflow variability are important factors for stream biota (Gordon and others, 1992, p. 17). The preceding section of this report introduced chemical water quality and summarized one of its constituents. In this section, selected physical and biological features of stream ecology in the YRB is discussed.

Physical Stream Habitat

The physical character of rivers within the study unit changes markedly from headwater streams to lowland streams. Upstream reaches are characterized by turbulent flows, steep gradients, cold water temperatures, coarse substrates, and well-oxygenated water, whereas lowland reaches are typically characterized by warmer water temperatures (especially during summer), gentle gradients, turbidity, sediment deposition, fine substrates, and smaller concentrations of dissolved oxygen.

The physical factors that are of greatest ecological significance include streamflow (discharge and velocity), channel shape, channel substrate, and water temperature (Gordon and others, 1992). Stream discharge, including the ecologically important periods of floods and droughts, was discussed in a previous section of this report. Streamflow velocities are a function of flow depth and gradient or slope in the downstream direction. To allow comparison of streamflow velocities among different sites or streams, a discharge of approximately constant frequency of occurrence is referenced at all sites; commonly, the mean annual discharge is used.

Leopold and Maddock (1953) tabulated mean streamflow velocities at mean annual discharge for 46 streamflow-gaging stations in the YRB, and several summary observations may be made from those data, as follows. Average velocity increases in the downstream direction along the upper through middle reaches of the principal rivers, as it does typically due to increasing flow depths. But velocities decrease in the lower reaches of the Bighorn, Powder, and Yellowstone Rivers. The Wind/Bighorn River mainstem has an average velocity between 0.9 and 1.1 m/s for much of its length upstream from Bighorn Lake, but on the Great Plains the Bighorn and Little Bighorn Rivers have average velocities of about 0.7 m/s. Also on the Great Plains, average velocities in the several forks of the Powder River near their confluences with the mainstem are less than 0.6 m/s. In a middle section of the Powder River mainstem, average velocity increases to about 1.0 m/s, but then decreases to less than 0.9 m/s in its lower reaches. In contrast, average velocity in the Yellowstone River at Corwin Springs, Mont., is 1.1 m/s, and increases to 1.5 m/s at Billings, Mont., but then decreases to just less than 1.0 m/s at Sidney, Mont. (Leopold and Maddock, 1953).

The streamflow velocities actually encountered by biota are more relevant than average velocity. But large local variability produces a mosaic of velocity patterns that support species with differing preferences (Gordon and others, 1992, p. 20). The velocity patterns, and related turbulence of flows, are difficult to quantify for an individual river, much less over a large drainage such as the YRB.

Channel shape is a function of the width and depths of streamflow. As related to flow depth, it influences water temperature, light penetration, and fish migration (where depth is too shallow for passage). As related to width, it influences the degree of shading by overhanging bank vegetation, instream photosynthesis, and input of organic matter (Gordon and others, 1992, p. 21). The width-to-depth ratio (W:D) commonly is used as an index of channel shape.

Osterkamp and Hedman (1982) presented channel geometry measurements, including active-channel width and average bankfull depth, for 21 stream stations in the YRB. For three streams with drainages primarily in the Wyoming Basin Province, W:D was 11.1 or less, indicative of incised channels. Seven cobble-bed streams with primarily mountainous drainages had W:D averaging 29.4 and ranging from about 20 to 51. On the Great Plains, six sand- or gravel-bed streams had W:D averaging 31.2 and ranging from 24 to 43 (Osterkamp and Hedman, 1982). Both of the sand-bed sites were on the Powder River. For comparison, sand-bed streams of some other Great Plains river systems (Platte and Republican Rivers) commonly have W:D greater than 100. The sand-bed channels of the Powder River contain more silt and clay in their beds than do those of the other two river systems, and such cohesive materials tend to provide greater resistance to erosion. The interrelations among physical habitat characteristics become apparent when seeking to understand the variation in these factors.

Stream substrate, or the particle-size distribution of bed material, is associated with streamflow velocity and, as implied above, influences channel shape. Substrate is an important factor controlling the occurrence of benthic (bottom-dwelling) fauna, and the complex mixture of coarse particles found in riffles provides the richest habitat for aquatic insects (Gordon and others, 1992). Although both the average and range of particle sizes, and their arrangement on the streambed, are ecologically important, data are most readily available for the median particle size (d_{50}).

In addition to substrate data for 19 stream stations in Osterkamp and Hedman (1982), the authors measured d_{50} for 15 stations while conducting a reconnaissance of YRB streams in 1997. These measurements were based on pebble counts performed using the half-largest-particle grid interval method of sampling (Wohl and others, 1996). Data from both sources were considered together to analyze the overall pattern of average particle sizes.

Three stations draining the Wyoming Basin Province have an average d_{50} of 6 mm, but substrates range from silt to coarse gravel. The exposed soil area around sparse vegetation in drier parts of the Wyoming Basin allows sheet-and-rill erosion to wash fine sediment into the stream channels.

Particle size generally decreases in the downstream direction, and data for the YRB streams are mostly consistent with this generalization. Among 15 stations with predominantly mountainous drainages, the average d_{50} is 125 mm, with substrates ranging from coarse gravel to medium boulders. Five stations that are transitional between mountains and plains drainages have median particle diameters ranging from 38 to 58 mm. On the Great Plains, the average d_{50} for 11 YRB stations is 12 mm, with substrates ranging from very fine sand to very coarse gravel. An exception to the trend of downstream fining of bed material occurs in the lower Powder River between Arvada, Wyo., and Locate, Mont., where d_{50} coarsens from 0.16 to 0.35 mm (Osterkamp and Hedman, 1982).

Water temperature varies both seasonally and daily in concert with air temperature, but it generally increases in the downstream direction as the cooler, high-elevation climate is displaced by the lowland climate. This pattern is seen in YRB streams, particularly with respect to mean water temperature in the warmest months. Available USGS data for the 14 stream stations listed in table 6, and for the Gardiner River near Mammoth in Yellowstone National Park, were summarized by month. The period of record used generally was 1970-94, although the period was slightly different for a few stations; however, for the Gardiner River, the record extends from 1985-96. Mean water temperature is warmest in July, with five exceptions: August has warmer mean water temperature than July for sites 5, 6, 28, 46 (fig. 12), and for the Gardiner River site. Site 46 has equally warm mean water temperature in June and August; all other sites have a single peak on the curve of monthly mean temperatures. Mean water temperature in the warmest month ranges from about 16.5^{o}C at sites 3 and 5 to about 23.5^{o}C at sites 35, 41, and 42.

Mean water temperature is coolest in January, with five exceptions: February has cooler mean water temperature than January for sites 6, 28, 42, and 45, and December has the coolest mean water temperature for the Gardiner River site. Mean water temperature in the coolest month generally has a small range, from 0^{o}C at sites 12, 13, 35, and 46 to about 1.3°C at sites 5, 6, and 28. In contrast, the geothermally influenced Gardiner River has warmer mean water temperatures for December through February, ranging from 10.3°C to 11.3°C. Cold winter water temperatures in the northeastern part of the YRB reflect a continental climatic gradient, whereas those in the Wind River Basin are indicative of its higher elevation.

Aquatic Biological Communities

Longitudinal Zonation

Longitudinal zonation of species occurs primarily with respect to altitude, water depth, and substrate composition in relation to stream gradient. High-gradient headwater streams are termed “salmonid” (after Family Salmonidae--Trouts, includes whitefishes, trouts, salmons, chars, and graylings) or rhithron zones, whereas lowland streams are termed “cyprinid” (after Family Cyprinidae--Minnows, includes minnows, shiners, dace, and chubs) or potamon zones. A transition zone, characterized by intermediate levels of both erosion and deposition, moderate gradients, alternating riffle-pool sequences, and sand-gravel substrates separates the two.

Biotic zonation was originally defined by the apparent relation between a stream’s gradient and the fish species harbored therein. However, algae and invertebrate studies have since shown that the complete assemblage of fauna shows zonation, both in community composition and in numbers of species (Hynes, 1970). For example, Newell (1977) sampled macroinvertebrate communities at 20 stations along the Yellowstone River. He defined the salmonid zone to extend downstream to about 680 km upstream of the mainstem mouth, and the transition zone to extend 200 km further downstream to the confluence with the Bighorn River. Newell’s (1977) downstream boundary for the salmonid zone roughly corresponds to the physiographic transition from mountains to plains.

Downstream variations in aquatic biota also have been explained using the river continuum concept (Vannote and others, 1980), relating stream order (Strahler, 1957), size of particulate organic matter, and the ratio of photosynthetic production to community respiration. Low-order streams (for example, first-order tributaries in the forested headwaters of the Yellowstone River) typically receive substantial terrestrial contributions of coarse particulate organic matter (CPOM) and have little photosynthetic production. Food chains in intermediate-sized streams are more dependent on photosynthetic production along with fine particulate organic matter (FPOM) from upstream shredding of CPOM by invertebrates (Newell, 1977). Greater turbidity in large rivers (such as downstream reaches of the Powder and Yellowstone Rivers) limits photosynthetic production such that FPOM becomes the principal base of the food chain.

Algae

Algae are ubiquitous, autotrophic, unicellular or multicellular organisms maintaining reproductive characteristics that distinguish them from liverworts, mosses, and vascular plants. Algae are central to aquatic ecosystems (Bahls and others, 1984) as producers of carbohydrates and proteins via photosynthetic processes and are an essential component of the riverine food chain (Round, 1973). Benthic species are most important when considering a stream’s primary production and plant diversity, and may be of epilithic (attached to stones), epipelic (attached to mud or sand), epiphytic (attached to plants), or epizoic (attached to animals) habits (Bold and Wynne, 1985). In flowing water, planktonic (open water) algal species are of lesser biological significance because their presence depends largely upon flow regime, catastrophic drift, and tributary inoculation.

In a variety of ways, algae and other photosynthetic plants are indicative of stream water quality (Whitton, 1979). Historically, biologically based surveys of streams, as opposed to those of lakes and reservoirs, have used animals, both vertebrates and invertebrates, as indicators. However, as pollutant concentrations meeting standards formulated to protect fish may be lethal to other aquatic species, modern bioassays generally use at least three food-chain components: algae, invertebrates, and fish or amphibians (Whitton, 1979). Changes in algal community structure, population, biomass, photosynthetic and respiration rate, nitrogen-fixation rate, chemical composition, and morphology may all signify water-quality changes within a given reach. Similarly, water quality may be questionable if a widely distributed species is not found during sampling (Bahls and others, 1984). A stream’s general water quality may best be indicated by benthic organisms.

Discharge, current velocity, substrate, turbidity, scour, suspended solids, nutrient status, dissolved oxygen, dissolved salts, light intensity, pH, hardness, toxicants, water temperature, and grazing animals are all factors influencing riverine algal communities. Community structure is strongly affected by the seasonal periodicity of species, with annuals achieving maximum development, abundance, and reproduction during specified seasons, perennials maintaining a continuous vegetative cycle, and ephemerals appearing, opportunistically, for short times during any season (Smith, 1950). Correspondingly, dispersal agents (such as wind, birds, amphibia) (Smith, 1950), catastrophic events, origin of water (spring, standing, or tributary), and riparian vegetation will vary community composition (Round, 1973; Bahls and others, 1984). Lastly, although limited algal species succession occurs, the traditional plant community concept as defined by terrestrial ecologists does not generally apply to streams; algal associations are difficult to delimit.

The divisions of algae most common in the YRB include:

- Bacillariophyta (diatoms) -- Diatoms are the predominant algae in streams draining the montane portions of the YRB (Robinson and others, 1996). Diatoms are essentially cold-water organisms, common during spring and autumn, and live on substrates including rock, sand, mud, and water plants, or as epiphytic growth on other algae. Planktonic habits of these essentially unicellular algae also are known (Bold and Wynne, 1985).
- Charophyta (stoneworts) -- These algae are usually found in freshwater, anchored on muddy or sandy substrates or hard limestone stream beds (Bold and Wynne, 1985). Many species become encrusted with carbonates, mainly of calcium and magnesium; hence suggesting their common names (stoneworts or brittleworts). Some species prefer brackish water, but most thrive best in clear, hard water; aeration is not essential.
- Chlorophycota (green algae) -- These algae are found in a variety of settings including standing, tranquil, and swiftly flowing water (cataracts, waterfalls, dam spillways). They inhabit water having a great range of salinity, and both benthic and planktonic species are known (Bold and Wynne, 1985).
- Chrysophyta (golden-brown algae) -- These algae typically are restricted to unpolluted, cold streams and springs.
- Cyanophycota (blue-green algae) -- These algae are generally more abundant in neutral or slightly alkaline water, but are found in water having a great range of salinity and temperature (Bold and Wynne, 1985). Both planktonic and benthic species are included in this division. Blue-green algae inhabit alkaline hot springs in Yellowstone National Park having water temperatures as warm as 74^{o}C (Bold and Wynne, 1985).
- Euglenophycota (euglenoids) -- These single-celled algae are widely distributed, being found in freshwater, brackish water, and on moist soils and mud (Bold and Wynne, 1985). Euglenoids usually are abundant in small pools rich in organic matter, especially those to which livestock have access.
- Pyrrophycophyta (dinoflagellates) -- Although generally marine, freshwater dinoflagellates occur in pools, ditches, and small lakes with considerable vegetation. The unicellular algae of this division are widely known for the blooms known as “red tides” that they produce in some marine locations.
- Rhodophycota (red algae) -- Although generally marine, freshwater species are restricted to cold, well-aerated water of rapids, falls, and spillways (Bahls and others, 1984). Many species do not appear reddish at all, and a full range of pigmentation occurs among freshwater species (Bold and Wynne, 1985).
- Xanthophyta (yellow-green algae) -- In streams, habits of these algae are epiphytic; terrestrial members of this division may be found growing in dense stands on drying mud along stream banks.

Algae found in cold, mountain streams within the YRB are more distinctive, and include a larger percentage of species restricted to a particular habitat, than those found in warmer, lowland streams (Smith, 1950). Algae found in rapids and waterfalls usually are attached to stones (Smith, 1950). Additionally, rocks continuously moistened by spray from rapids and waterfalls, or where there is a continuous trickle of water, develop extensive feltlike or gelatinous algal masses upon rocky cliffs (Smith, 1950). Certain species of blue-green algae are the most frequently encountered algae on dripping cliffs (Smith, 1950). Algae of high-gradient streams are of two distinct morphological types: encrusting algae (diatoms, for example) and those in which the greater part of the thallus (undifferentiated body) trails in the current (Smith, 1950). Certain red algae and river mosses (*Cladophora*) are restricted to cold, high-gradient streams at elevations higher than approximately 3600 m (Smith, 1950).

The algal flora of lowland streams with fine-grained substrates are far less diverse than those of mountain streams (Smith, 1950). Most lowland flora are attached to mud or sand, and include diatoms, blue-green algae, green algae, and euglenoids. In contrast to encrusting and trailing algae upstream, these species are often motile.

Invertebrates

As with algae, the composition of invertebrate communities varies longitudinally downstream within the YRB. Overall, factors influencing both distribution and abundance of aquatic invertebrates include current velocity, water temperature, substrate, stability of both aquatic and riparian vegetation, dissolved substances, competition, zoogeography, food, disturbance history, and human practices. Water temperature and chemistry exert great influence, but invertebrate morphological features and respiratory requirements, in relation to streamflow habitat, ultimately define macroinvertebrate community composition. Large, stable substrates such as boulders and cobbles support larger, more productive invertebrate populations than do unstable gravel and sand substrates. Consequently, a longitudinal decrease in substrate size and riffle frequency results in lower macroinvertebrate production and diversity downstream. Although deposition of organic sediment at slow current velocities may increase benthic production for midges (*Chironomidae*) and earthworms (*Oligochaeta*) that depend on allochthonous detritus (Baril and others, 1978), the filling of interstitial spaces with fine, inorganic sediment eliminates potential habitat.

Within the YRB, invertebrate fauna are likely be dominated by mayflies (*Ephemeroptera*, includes both mountain and prairie varieties) whose current-velocity preferences vary; for example, *Baetis* prefer rapid currents whereas *Tricorythodes* prefer slow velocities. Other prominent taxa include caddisflies (*Trichoptera*), many of whom, such as *Hydropsyche*, depend on rapid currents for proper net functioning (Baril and others, 1978); true flies (*Diptera*) (Newell, 1977); and stoneflies (*Plecoptera*), whose general preference is for rapid currents and whose fauna is diverse but not abundant (Newell, 1977). Another swift-current specialist is the riffle beetle (*Elmidae*). Invertebrates present in large numbers in transition-zone streams of the YRB generally are tolerant of a wide range of habitat conditions, whereas those abundant in prairie reaches are considered tolerant of turbid, silty conditions (Baril and others, 1978).

Macroinvertebrate distribution and abundance often vary widely through the year in response to seasonal flow variations. Dispersal is affected by floods through channel scouring and catastrophic drift that can transport invertebrates that would not drift otherwise (Peterson, 1990). Broadly, within each ecoregion of the YRB (described later and shown in fig. 23), invertebrate communities of all perennial streams will be similar; moreover, communities of ephemeral and intermittent streams will resemble one another (Peterson, 1990).

Fish

The distribution of fish within the YRB is influenced by elevation, drainage divides, and other physiographic features (Baxter and Stone, 1995). As with other aquatic communities, both abiotic and biotic factors control the occurrence, interspecific relationships, numbers, and growth rates of fish. Abiotic factors include dissolved oxygen, water temperature, current velocity, discharge fluctuation, dissolved salts, substrate, and turbidity. Information on the effect of biotic factors (numbers and growth rates of competitors) is much less available, although closely related species interact with one another in such a way as to divide habitat between them (Hynes, 1970). Of abiotic factors, water temperature is important to cold- and warm-water fish species and indirectly influences oxygen consumption; water chemistry seems to be of lesser importance in natural systems (Hynes, 1970).

Warm-water species considered native to the YRB include the goldeye, brassy minnow, fathead minnow, flathead chub, sturgeon chub, western silvery minnow, white sucker, shorthead redhorse, stonecat, burbot, channel catfish, and sauger. Of these, the stonecat may be found in high-gradient reaches while the goldeye, flathead chub, western silvery minnow, burbot, and sauger all prefer larger, sluggish, deeply turbid streams. The channel catfish prefers larger rivers with turbid habitats. The shorthead redhorse, white sucker, brassy minnow, fathead minnow, and sturgeon chub may all be found in transition zones that generally have less turbidity, some vegetation, and gravel substrates.

Cold-water species native to the study unit but also found on the western side of the Continental Divide include the mountain whitefish, cutthroat trout, arctic grayling, and mottled sculpin. Species common to cool-water, transition-zone streams include the lake chub, longnose dace, longnose sucker, mountain sucker (Brown, 1971; Baxter and Stone, 1995). Of these, the lake chub is usually found in smaller streams, and the mountain sucker inhabits a wide variety of habitats, including large rivers and mountain streams. The longnose dace prefers the swift-water environment of riffles, and the longnose sucker prefers clear water.

In the YRB, several species of fish are accorded special concern by the Federal or State governments. The pallid sturgeon, a Federally listed Endangered Species, occurs in the lower Yellowstone River. The sturgeon chub and arctic grayling currently are designated as Candidate species for Federal Endangered or Threatened status (Fertig, 1997). The Yellowstone cutthroat trout is designated a Sensitive Species by the U.S. Forest Service. Species of special concern to State governments include the pallid sturgeon, paddlefish, Yellowstone cutthroat trout, arctic grayling, sturgeon chub, sicklefin chub, northern redbelly x finescale dace (hybrid), and blue sucker. Most of these are warm-water species inhabiting the lower Yellowstone River, but the Yellowstone cutthroat trout and the arctic grayling are cold-water species.

Ground Water

The hydrologic and water-quality characteristics of ground water in the study unit differ with location, elevation, and geologic unit. The physical and geochemical properties of the rock units comprising the aquifers to a large extent determine the quantity and quality of ground water available for use. The primary aquifers in the YRB are unconsolidated Quaternary deposits, lower Tertiary rocks, and rocks of Mesozoic and Paleozoic age. Aquifers are located throughout most of the study unit (fig. 16). The unconsolidated Quaternary deposits and lower Tertiary rocks are found primarily in the structural basins, whereas the Mesozoic and Paleozoic units are at or near the surface chiefly in the uplifted areas of the YRB. The lower Tertiary aquifers have the greatest surface extent in the study unit. The quality of ground water in shallow aquifers may be influenced by the quality of nearby surface water, such as lakes and streams. The areal distribution of the uppermost principal aquifers in semiconsolidated and consolidated rocks of the study unit is shown in figure 16.

The four major structural basins of the YRB--the Wind River, Bighorn, Powder River, and Williston Basins (fig. 5)--each contain substantial quantities of ground water and will be the focus of this section. The remainder of the study unit is composed of small basins, structural uplifts, and mountain ranges that contain smaller quantities of ground water. Ground-water resources in these regions will not be discussed in this report.

Wind River Basin

The Wind River Basin contains both confined and water-table aquifers. The Wind River Formation of Eocene age and older sedimentary rocks often yield water under confined conditions. In alluvial and eolian sand deposits of Quaternary age, unconfined (water-table) conditions often prevail (Whitcomb and Lowry, 1968). The physical and water-bearing characteristics of the geologic formations in the Wind River Basin are summarized in table 16 (at end of report). The following text briefly summarizes the hydrologic characteristics of the rock units within the Wind River Basin. For a more complete description the reader is referred to Whitcomb and Lowry (1968), Richter (1981), Plafcan and others (1995), and Daddow (1996).

Quaternary Aquifers

Whitcomb and Lowry (1968) report that coarse sand and gravel beds in the valleys of perennial streams whose headwaters are in the Wind River and Owl Creek Mountains, are capable of yielding moderate to large quantities of water. Generally, the concentration of dissolved solids in the upper reaches of floodplain deposits of perennial streams is less than that in deposits further downstream. For example, a well drilled in the alluvium of the central Wind River valley yielded a calcium bicarbonate water that contained 272 ppm (parts per million) of dissolved solids, whereas a well about 16 miles downstream yielded a sodium sulfate

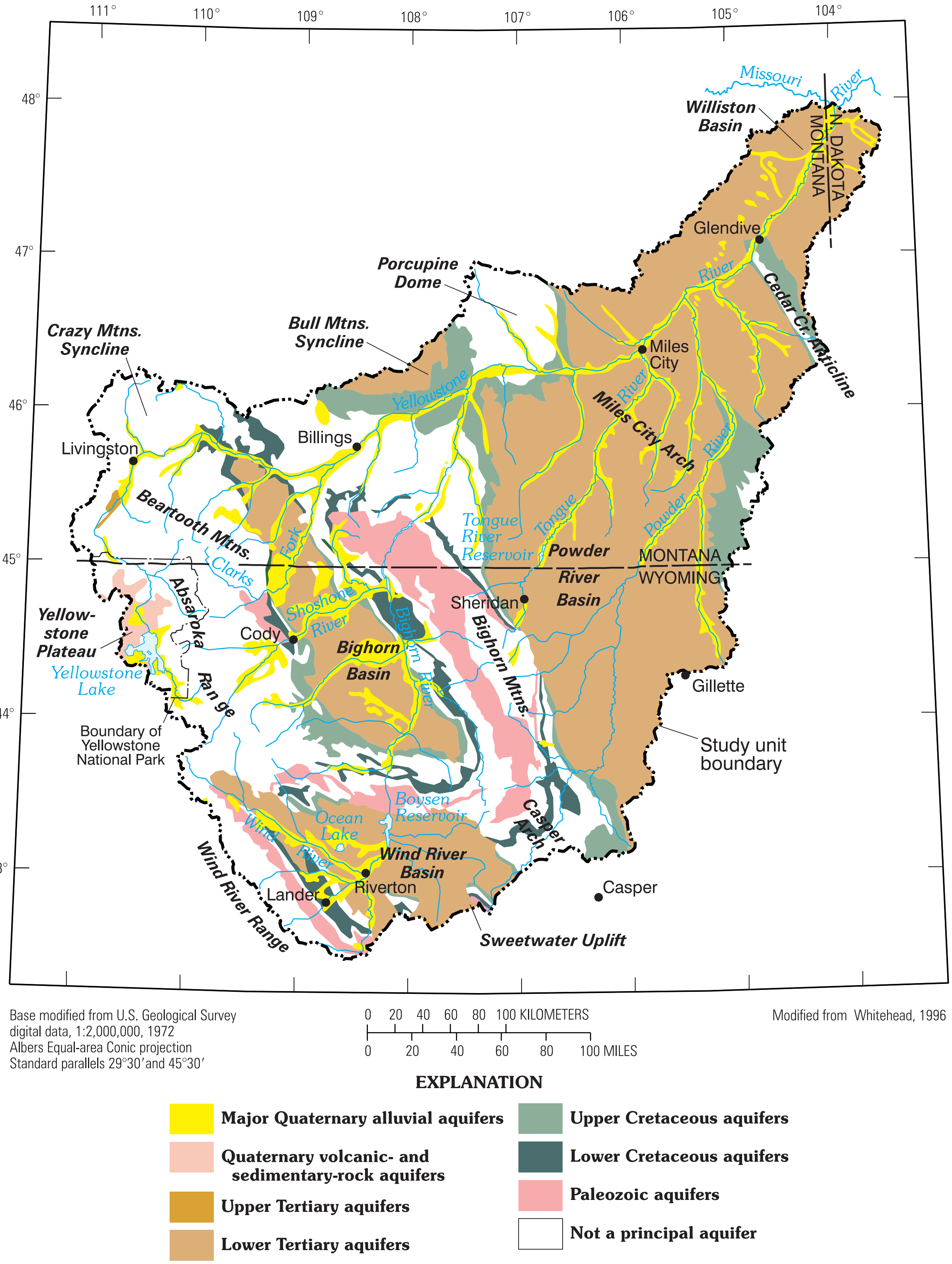


Figure 16. Generalized aquifers in semiconsolidated and consolidated rocks located at or near the land surface, Yellowstone River Basin, Montana, North Dakota, and Wyoming.

water that contained 1,230 ppm of dissolved solids (Whitcomb and Lowry, 1968). Large-scale development of this water resource has not occurred because surface-water supplies generally are adequate for present needs.

According to Whitcomb and Lowry (1968), alluvial deposits located along ephemeral and intermittent streams that originate within the Wind River Basin generally consist of fine to coarse sand intermixed with silt and clay. Wells in these deposits normally only yield enough water for stock and domestic use. Recharge to these aquifers is mainly from infiltration of precipitation on the drainage area, and the amount of ground water available to wells fluctuates accordingly.

Terrace deposits can yield adequate quantities of water for stock or domestic use in areas where surface water has been applied for irrigation. Yields fluctuate in response to irrigation, and some of the shallower wells go dry during the winter (Whitcomb and Lowry, 1968).

In the northeastern part of the basin, Whitcomb and Lowry (1968) reported that deposits of eolian sand are an important source for stock and domestic supplies of ground water. The water in these deposits is generally derived from local infiltration of precipitation.

Tertiary and Cretaceous Aquifers

According to Whitcomb and Lowry (1968), the major Tertiary aquifers in the Wind River Basin are the Split Rock Formation of Oligocene and Miocene age and the Eocene Wind River Formation. The Oligocene White River Formation has similar hydrologic characteristics as the Split Rock Formation but has not been widely developed as a ground-water source because shallower aquifers usually provide adequate water for stock and domestic uses. The Tepee Trail, Aycross, and Indian Meadows Formations of Eocene age, together with undifferentiated rocks of Tertiary age, may yield moderate to large supplies of water, but these rocks have not been tested as a potential source of ground water.

Cretaceous aquifers generally are not used for ground-water supplies throughout the basin for several reasons. According to Whitcomb and Lowry (1968), although the water in these formations is usually under artesian pressure and piezometric surfaces are often near the land surface, the formations themselves lie at great depths except around the margins of the basin and in areas of local uplift. The formations principally consist of shale containing minor amounts of fine-grained silty sandstone and generally have low permeabilities. The Upper Cretaceous Lance Formation and the Lower Cretaceous Cloverly Formation have more suitable aquifer characteristics, but areas in which the formations lie within economical drilling depths are small. Water from the Mesaverde Formation, Cody Shale, and Frontier Formation is generally unsuitable for domestic use, and in some wells it is so unpalatable that stock will not drink it (Whitcomb and Lowry, 1968).

Pre-Cretaceous Aquifers

Pre-Cretaceous formations are used to a limited extent as supplies of ground water in the basin. Whitcomb and Lowry (1968) reported that many of the formations have suitable aquifer characteristics but occur below economical drilling depths in most of the Wind River Basin. The formations form narrow outcrops on the flanks of the Wind River, Owl Creek, and Bighorn Mountains and in some of the major anticlinal structures within the basin. The Jurassic Morrison and Sundance Formations, the Triassic Chugwater Formation, the Permian Phosphoria Formation and related rocks, the Pennsylvanian Tensleep Sandstone, and Mississippian Madison Limestone are used in small areas of the basin as ground-water supplies. Pre-Mississippian rocks in the basin are unused because of great burial depths and inaccessibility in outcrop areas.

Bighorn Basin

The Bighorn Basin contains both artesian and water-table aquifers. Aquifers in Quaternary unconsolidated deposits are generally unconfined, and the water table is generally at shallow depths. Water in bedrock aquifers occurs under either confined or unconfined conditions (Plafcan and others, 1993). The physical and water-bearing characteristics of the geologic formations in the Bighorn Basin are summarized in table 16 (at end of report). The hydrologic characteristics of the rock units within the basin are briefly summarized in the following two sections. For a more complete description the reader is referred to Lowry and others (1976), Libra and others (1981), Plafcan and others (1993), Susong and others (1993), and Plafcan and Ogle (1994).

Quaternary and Tertiary Aquifers

Holocene and Pleistocene unconsolidated deposits in the Bighorn Basin include floodplain alluvium, terrace deposits, pediments, minor colluvium, and alluvial fan deposits. The floodplain alluvium is generally less than 10 m thick. Alluvial and colluvial deposits located along the larger streams, such as the Bighorn and Shoshone Rivers, are among the most productive and predictable sources of ground water in the basin (Plafcan and others, 1993; Susong and others, 1993).

Lower Tertiary aquifers in the Bighorn Basin are used primarily as a drinking-water source for residents without access to a public drinking-water supply (Libra and others, 1981). The areally extensive Willwood Formation of Eocene age is the principal Tertiary aquifer in the basin. The sandstone content of the formation ranges from 3 to 88 percent with the average being 25 percent. Ground water occurs in sandstone lenses that are often small, making it difficult to locate productive wells for stock or domestic uses (Plafcan and Ogle, 1994; Plafcan and others, 1993; Susong and others, 1993).

The Paleocene Fort Union Formation is a minor aquifer in parts of the basin. The average sandstone content is 25 percent, but sandstone lenses are seldom continuous for more than a few hundred yards. The formation is used as an aquifer primarily where it crops out west of the Bighorn River (Plafcan and Ogle, 1994; Plafcan and others, 1993; Susong and others, 1993).

Mesozoic and Paleozoic Aquifers

Cretaceous aquifers have not been widely developed throughout the basin, although the Upper Cretaceous, Lance, Mesaverde, and Frontier Formations have potential for more extensive development (Plafcan and others, 1993). Jurassic and Triassic sandstones are locally used as aquifers. The Gypsum Spring Formation of Jurassic age consists of interbedded red shale, dolomite, and gypsum (table 16, at end of report). Solution of gypsum in this formation may provide enough secondary porosity to provide high yields to wells in some areas (Lowry and others, 1976). Mesozoic rocks generally do not occur at economical drilling depths except at the margins of the basin and along areas of structural uplift.

The major Paleozoic aquifers in the basin include the Pennsylvanian Tensleep Sandstone, the Mississippian Madison Limestone, the Ordovician Bighorn Dolomite, and the Cambrian Flathead Sandstone (Plafcan and Ogle, 1994; Plafcan and others, 1993; Susong and others, 1993). These aquifers are confined by overlying Mesozoic shales as well as by impermeable Paleozoic strata such as the Goose Egg Formation of Triassic and Permian age, the Amsden Formation of Pennsylvanian and Mississippian age, the Ordovician Gallatin Limestone, and the Cambrian Gros Ventre Formation (Plafcan and others, 1993). Paleozoic aquifers in the Bighorn Basin are recharged primarily in the mountains on the basin margins. Except near basin margins and other areas of structural uplift, Paleozoic rocks do not occur at economical drilling depths (Plafcan and Ogle, 1994; Plafcan and others, 1993; Susong and others, 1993).

Powder River Basin

The physical and hydrologic characteristics of the geologic formations in the Powder River Basin are summarized in tables 16 and 17 (at end of report). The following two sections briefly summarize the hydrologic characteristics of the aquifers within the basin. For a more complete description the reader is referred to Crist and Lowry (1972), Hodson and others (1973), Lewis and Hotchkiss (1981), and Slagle and others (1984).

Quaternary and Tertiary Hydrogeologic Units

According to Lewis and Hotchkiss (1981), the shallow aquifer system of the Powder River Basin is composed of five mappable hydrogeologic units located stratigraphically above the regionally persistent and essentially impermeable Upper Cretaceous Bearpaw Shale. The uppermost hydrogeologic unit in the shallow aquifer system is the Wasatch-Tongue River aquifer (table 17, at end of report) (Lewis and Hotchkiss, 1981). The aquifer is extensive, thick (up to 1,190 m thick), and is exposed at the land surface in most of the basin. The depositional environments of the geologic units included in the aquifer are generally terrestrial. The average sand content of this unit is 54 percent, indicating it could be an aquifer over most of the area.

The Lebo confining layer (up to 920 m thick) extends over most of the basin and underlies the Wasatch-Tongue River aquifer (table 17, at end of report). The unit generally correlates with the Lebo Shale Member of the Fort Union Formation. The sand content of the unit has a mean value of 31 percent, indicating that it generally acts as a confining layer (Lewis and Hotchkiss, 1981).

The Tullock aquifer (up to 600 m thick) underlies the Lebo confining layer except near outcrop areas. With an average sand content of 53 percent the unit is considered an aquifer in most of the basin (Lewis and Hotchkiss, 1981).

Mesozoic and Paleozoic Hydrogeologic Units

The Cretaceous Upper Hell Creek confining layer (table 17, at end of report) underlies the Tullock aquifer (Lewis and Hotchkiss, 1981). The unit is a major confining layer throughout the basin, is up to 610 m thick, and has a mean sand content of 35 percent (Lewis and Hotchkiss, 1981).

The Upper Cretaceous Fox Hills-Lower Hell Creek aquifer (table 17, at end of report) underlies the Upper Hell Creek confining layer except at outcrop areas (Lewis and Hotchkiss, 1981). The aquifer is up to 780 m thick, has a mean sand content of 50 percent, and yields water to wells in most areas. The base of the aquifer is the top of the Bearpaw Shale (equivalent to Lewis Shale).

Several formations of the Lower Cretaceous Series in the basin consist of shales that are not usable as aquifers. However, the Cloverly, Fall River, and Lakota Formations contain sandstone aquifers, but are too deeply buried to be useful, except at the basin margins.

According to Hodson and others (1973), several Paleozoic formations, including the Minnelusa Formation and Tensleep Sandstone of Permian and Pennsylvanian age, and the Madison Limestone of Mississippian age, have great potential for ground-water development. The Bighorn Dolomite of Ordovician age and the Flathead Sandstone of Cambrian age also have potential. Although these Paleozoic formations would likely produce relatively high yields of ground water, they are largely unused because, except at the basin margins, they are deeply buried.

Williston Basin

Only a small, southwestern part of the Williston Basin is included in the study unit. The shallow hydrogeologic units of the Williston Basin included in the study unit are similar to the shallow hydrogeologic units of the Powder River Basin.

Stoner and Lewis (1980) mapped the shallow hydrogeologic units in southeastern Montana, including the southwestern part of the Williston Basin. The shallow aquifer system was divided into mappable units (table 18, at end of report) that are similar to those mapped by Lewis and Hotchkiss (1981) in the Powder River Basin. The most notable difference between the aquifer units defined in the Williston Basin and those in the Powder River Basin occurs in the upper part of the shallow aquifer system. The aquifers lying above the Lebo confining layer in the Williston Basin are divided into four separate mappable units, whereas in the Powder River Basin they are grouped as a single unit. For a more complete description of the shallow aquifer system in the Williston Basin the reader is referred to Stoner and Lewis (1980), and Slagle and others (1984).

Anthropogenic Factors

The term “anthropogenic” means of, relating to, or involving the impact of humans on nature. Because human practices are the source of many water-quality contaminants in the YRB, they must be described as an integral part of the environmental setting. Agricultural runoff, urban runoff, point discharges of municipal and industrial wastes, mine drainage, septic-system effluent, landfill leachate, and contaminated atmospheric deposition are all sources of anthropogenic contamination in the study unit. These sources are directly related to population density, land cover and land use, water use, and waste disposal in the YRB. The major contaminants associated with human activities are summarized in table 8.

Population

The early human populations of the YRB included the Crow Nation, which had pushed westward as far as the mouth of the Bighorn River in the mid-1700s, and by 1800 had displaced the Shoshone Tribe throughout the entire upper YRB (U.S. Department of the Interior, 1965). Fur trappers considered the YRB a prime area of production from 1805-35. However, permanent settlement by non-Native populations coincided with the mining booms, cattle drives, and westward railroad construction beginning in the 1860s. In 1874, commercial river boats began service on the

Table 8. *Human activities contributing to contamination of surface and ground water*

(modified from Risser and Siwiec, 1996, table 16)

Activity	Contaminants frequently cited as results of activity	Other remarks
Land-use activities		
Agricultural activities: applications of commercial fertilizers, manure, and pesticides	Nitrate, phosphate, bacteria, and pesticides	Surface erosion washes chemical residues into streams; infiltrating water transports dissolved contaminants to ground water
Mining activities: mining and spoil disposal	Acids, iron, manganese, sulfate, uranium, thorium, radium, molybdenum, selenium, and other trace elements	Leachates from spoil piles of coal, metallic-, and nonmetallic-mineral mining contain a variety of contaminants
Urban activities	Bacteria, hydrocarbons, dissolved solids, lead, cadmium, and other trace elements	Urban runoff washes contaminants into streams; infiltration from detention basins and drainage wells can reach ground water
Storage tanks	Petroleum products, acids, metals, and organic compounds	Useful life of steel tanks is 15-20 years; leaks, spills, and overflows may contaminate ground water
Waste disposal		
Septic systems	Bacteria, viruses, nitrate, phosphate, chloride, and synthetic organic compounds	None
Landfills	Dissolved solids, iron, manganese, trace elements, acids, organic compounds, and pesticides	Traditional disposal method used for municipal and industrial waste; number of abandoned landfills and dumps is unknown
Surface impoundments	Manure, trace elements, and organic compounds	Used to store agricultural wastes, industrial liquid wastes, municipal sewage sludge, and other wastes
Injection wells	Dissolved solids, bacteria, sodium, chloride, nitrate, phosphate, organic compounds, pesticides, and acids	Hazardous wastes also were injected in the past
Surface applications of waste	Bacteria, nitrate, phosphate, trace metals, and organic compounds	Waste disposal from municipal sewage-treatment plants, septic systems, and drinking-water treatment plants
Discharges from sewage-treatment plants	Bacteria, nitrate, ammonia, phosphate, organic compounds, and suspended solids	Base flow in receiving water body may be inadequate for proper dilution
Industrial discharges	Organic compounds and trace elements	Treated effluent in many cases; discharged to surface water

Yellowstone River as far upstream as present-day Billings, but were abandoned in 1884, 2 years after the railroad reached Billings (U.S. Department of the Interior, 1965). The frontier was considered closed by 1890, and within another 20 years much of the YRB achieved its maximum population density to date (Missouri Basin Inter-Agency Committee, 1969).

From 1900-90, the rate of population growth in this region has lagged behind the National average. The YRB is sparsely populated (fig. 17), and the population was relatively stable during the decades preceding 1990. Population density in 1960 was less than two persons per km^2 (Missouri Basin Inter-Agency Committee, 1969). From 1980-90 the population of the study unit decreased by about 2 percent (U.S. Bureau of the Census, 1980; 1991), and averaged less than two persons per km^2 in 1990.

According to the 1990 census, about 323,000 people resided in the study unit on April 1, 1990. The population distribution by State is 206,000 people in Montana, 116,000 people in Wyoming, and 1,000 in North Dakota. The major population center of the study unit is the Billings, Mont., metropolitan area, with a population of 113,419 in 1990 (U.S. Bureau of the Census, 1997c). No other cities in the YRB had a 1990 population greater than 14,000 residents (U.S. Bureau of the Census, 1997b). Gateway communities to Yellowstone National Park do not have a large resident population, but a substantial temporary population of visitors is typically present because of tourism and recreational opportunities. The summer seasonal peak of temporary population is pronounced.

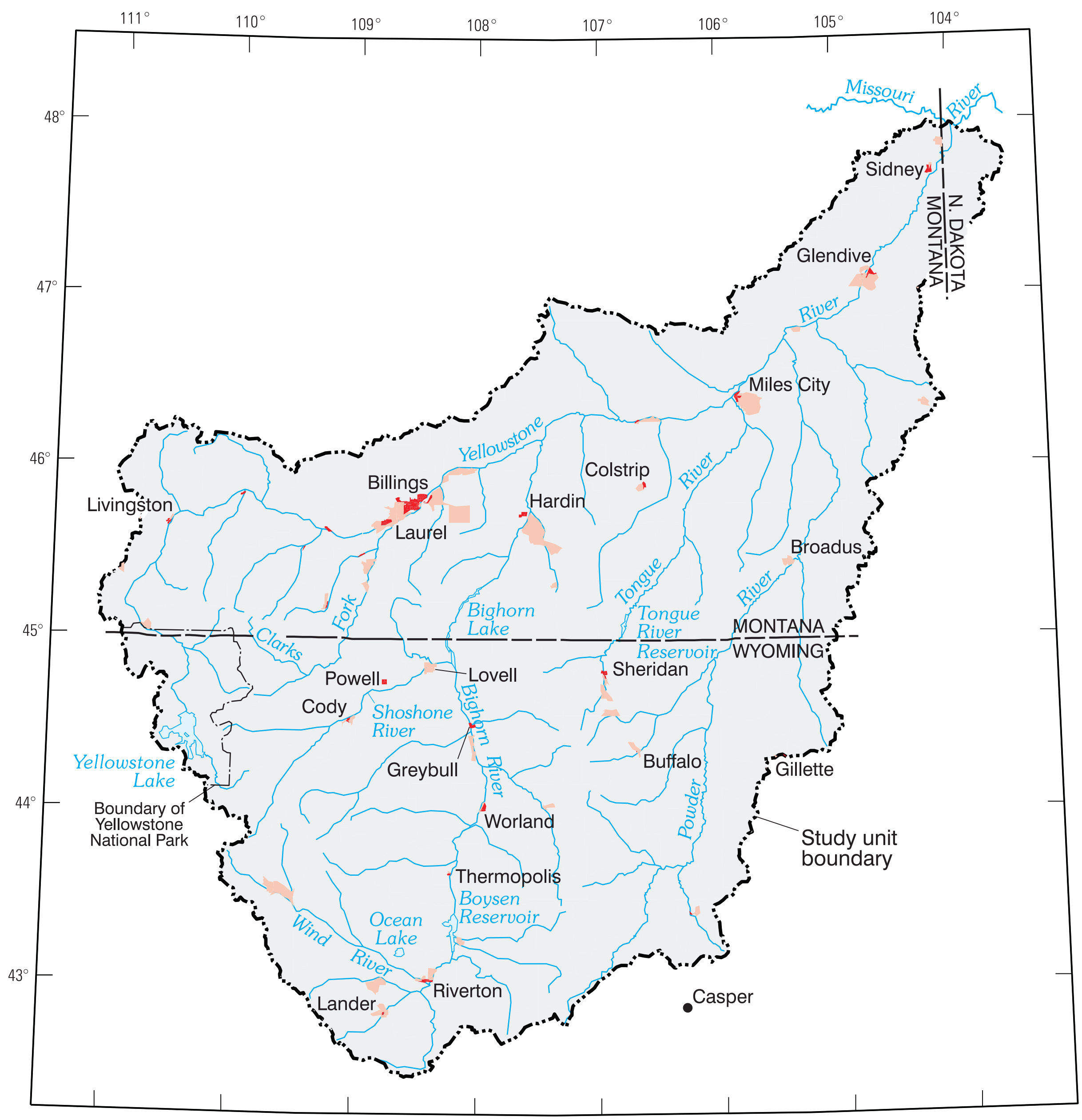
Population within the study unit is estimated to have increased by 8.4 percent since 1990 to about 350,000 by July 1, 1996. These population increases have been centered in several areas experiencing rapid growth, largely by the conversion of ranch land to low-density residential use. During 1990-96, the six county area generally corresponding to the northwestern YRB experienced an 11 percent increase in estimated population—an increase of about 19,000 residents, and about half of this growth occurred in Billings (U.S. Bureau of the Census, 1997a; 1997b). Several Wyoming communities along the eastern front of the Bighorn Mountains also have had 1990-96 population growth, averaging nearly 8 percent (U.S. Bureau of the Census, 1997b).

Land Cover and Land Use

Land-cover and land-use maps indicate the spatial distribution of management practices likely to affect the quality of water resources (Gallant and others, 1989). Activities such as grazing, logging, and mining on rangeland and forest land may affect water quality by increasing suspended-sediment loads and concentrations of metals or nutrients, and by altering hydrologic conditions. Pesticide and fertilizer applications, crop rotation, and tillage practices may affect both surface-water and ground-water quality on agricultural land. Water quality in urban areas is subject to runoff, pesticide and fertilizer usage, and waste disposal.

The available USGS data for land cover and land use (U.S. Geological Survey, 1986) are relatively detailed but also somewhat dated. The 1- by 2-degree quadrangles covering the YRB study unit were interpreted from aerial photography acquired during 1970-84 (U.S. Geological Survey, 1976-85). The USGS data (1:250,000 scale) are not a large-scale source, yet were the most spatially detailed with consistent coverage of the entire study unit. At the most general level of classification (Anderson and others, 1976), the land cover and land use of the YRB are shown in figure 18.

Agricultural, urban, and mineral-related land uses are discussed in separate sections that follow. Silviculture is another potentially important land-use activity. Forests cover about 20 percent of the YRB (U.S. Geological Survey, 1986). Most of the timber resources of the YRB are contained within the National Forest System lands. Each national forest has developed a Forest Plan that specifies the maximum volume of timber that may be sold from the suitable timber base during the specified planning period. For example, the allowable sale quantity (ASQ) of timber established by the 1986 Forest Plan of the Shoshone National Forest (fig. 19) was 11.2 million board feet per year on a suitable timber base of about 350 km^2 (U.S. Dept. of Agriculture, Forest Service, 1997) (One board foot equals 0.0929 m^2 [one foot square] by 25.4 mm [1 inch] thick). Following the wildfires of 1988, ASQs of timber were revised for some areas due to extensive burning of the timber base. Shoshone National Forest is currently using an ASQ of about 4.5 million board feet per year, and an additional 2.3 million board feet of other products (fuelwood, posts, and poles) are sold annually (U.S. Dept. of Agriculture, Forest Service, 1997).



Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-area Conic projection
Standard parallels 29°30′ and 45°30′

0 20 40 60 80 100 KILOMETERS
0 20 40 60 80 100 MILES

Modified from U.S. Bureau of the Census, 1991; and Hitt, K.J., U.S. Geological Survey, unpublished data, 1994

EXPLANATION

Population density, in persons per square kilometer

- Less than 5
- 5 to 100
- More than 100

Source: U.S. Bureau of the Census, 1991

Figure 17. Population density by census block group, 1990, Yellowstone River Basin, Montana, North Dakota, and Wyoming.

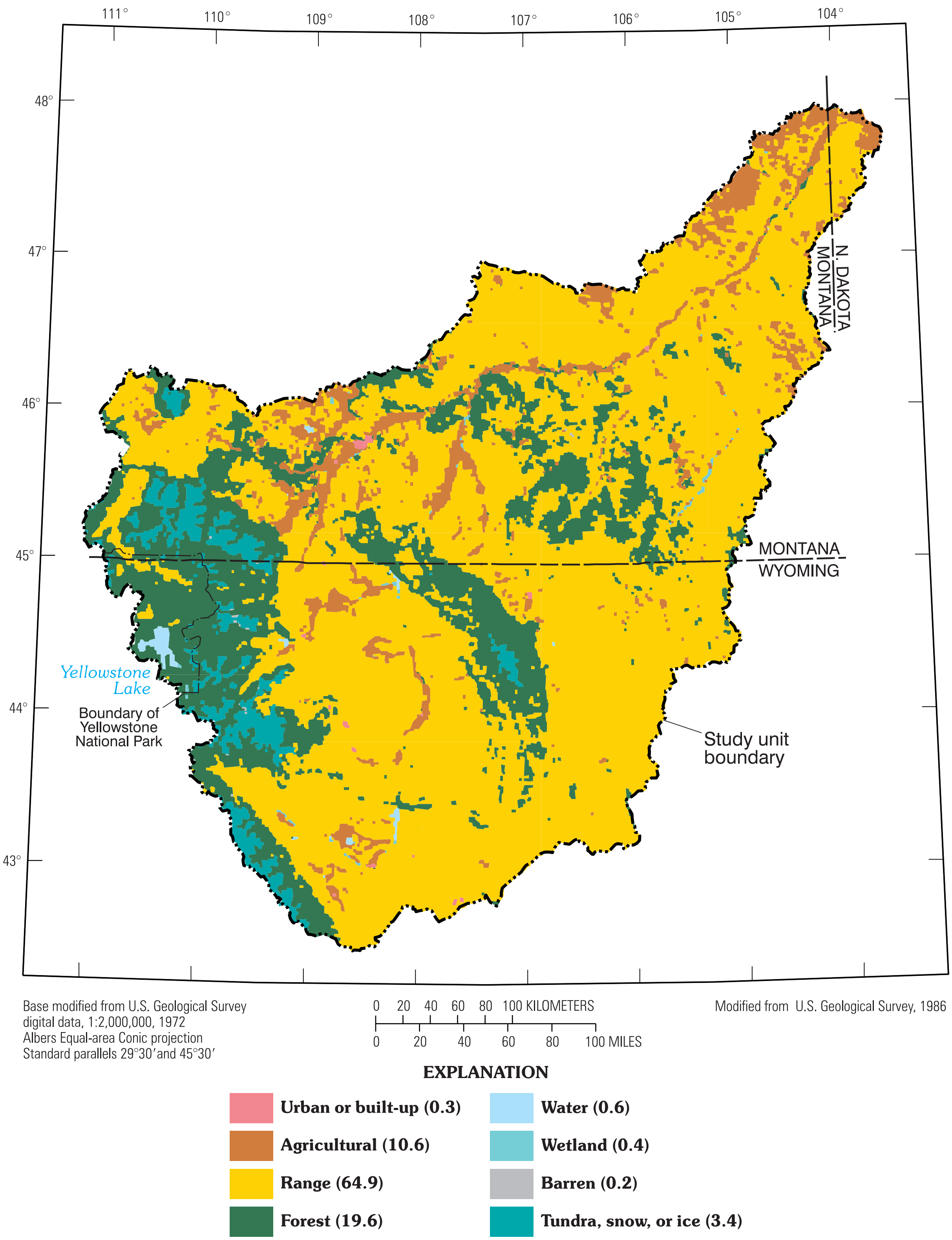
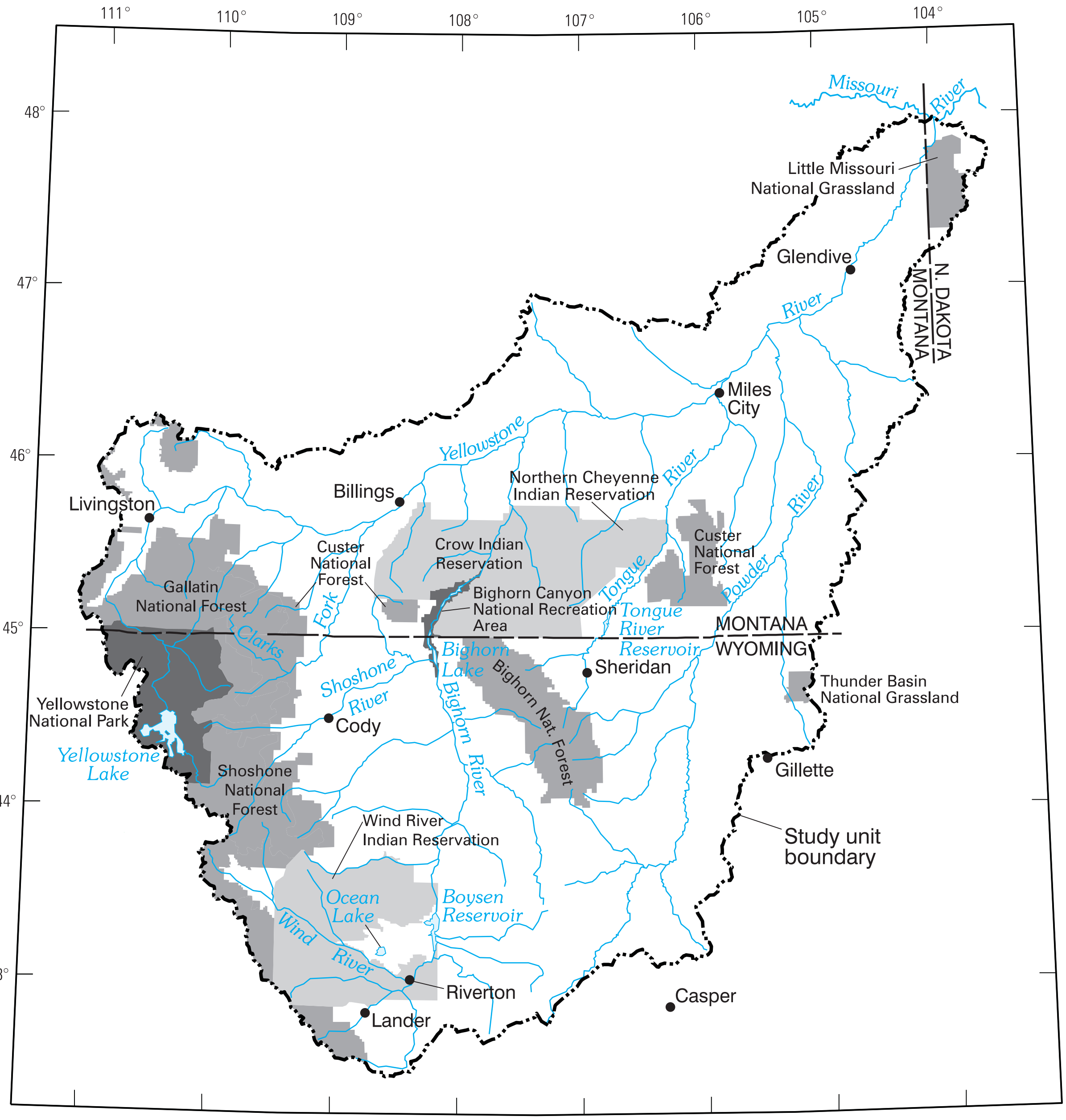


Figure 18. Land cover and land use, Yellowstone River Basin, Montana, North Dakota, and Wyoming (area, as percentage of study unit).



Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972
Albers Equal-area Conic projection
Standard parallels 29°30′ and 45°30′

0 20 40 60 80 100 KILOMETERS
0 20 40 60 80 100 MILES

Modified from U.S. Geological Survey, 1970b

EXPLANATION

- **Indian reservation**
- **National forest or grassland**
- **National park or recreation area**

Figure 19. Indian reservations, national forests and grasslands, and national parks and recreation areas, Yellowstone River Basin, Montana, North Dakota, and Wyoming.

Agriculture

Agricultural activities, primarily livestock production and irrigated and dryland crop production, are the most areally extensive land-use industries in the study unit. Rangeland is the dominant land cover, with about 43 percent of the study unit composed of subhumid grassland and semiarid grazing land, about 16 percent grazed desert shrubland, and about 5 percent grazed open woodland. Cropland and pasture compose only about 11 percent of the study unit (U.S. Geological Survey, 1986), with about 36 percent of the harvested cropland in 1987 having been irrigated (Battaglin and Goolsby, 1994). Most irrigated cropland is located in the principal stream valleys.

The effects of agriculture on sediment, nutrient, bacteria, and pesticide concentrations are water-quality issues in the study unit. Grazing, especially when pasture or rangeland are stocked near or above their carrying capacities, has been shown to increase runoff and soil erosion as vegetative land cover decreases and stream banks become trampled (Owens and others, 1996). Even near-natural rangelands, such as those within national parks, may be subject to overgrazing, particularly when humans apply various management strategies to modify populations of herbivorous wildlife (Coughenour and Singer, 1991).

According to the 1987 Census of Agriculture, 9,584 farms covered 117,367 km^2 in the YRB, of which 4,023 km^2 was irrigated land. Cropland accounted for 15,011 km^2 of this area, in which wheat (2,891 km^2), alfalfa (2,231 km^2), barley (1,249 km^2), hay other than alfalfa (1,089 km^2), corn (268 km^2), oats (214 km^2), and sugar beets (165 km^2) were the principal crops harvested (Battaglin and Goolsby, 1994). A total of 8,360 km^2 of cropland was harvested in 1987. Pasture, along with 1,971 km^2 of woodland, composed the remainder of the farmland. The predominant crop rotation in the Wyoming part of the YRB is barley and sugar beets, with some producers also including corn and alfalfa as part of their rotation (P. Shelton, USDA Natural Resources Conservation Service, Casper, Wyo., written commun., 1998).

Commercial fertilizers (see table 9) were applied to 4,758 km^2 of cropland. Estimates of commercial fertilizer usage do not include manure applications. Nutrients from manure are a potential problem because animal densities are high in localized areas. Although records are not kept of manure applications, the domestic livestock in the study unit (table 10) are counted regularly. Cattle raised for beef are the most numerous group of domestic livestock, followed by sheep, hogs, and poultry.

Table 9. *Estimated annual applications of fertilizers in the Yellowstone River Basin*

(Modified from Battaglin and Goolsby, 1994)

Fertilizer used	Estimated application of active ingredient during 1987, in kilograms
Nitrogen fertilizers:	
Anhydrous ammonia	32,750,529
Urea	7,009,657
Miscellaneous forms	6,545,967
Nitrogen solutions	6,254,551
Ammonium nitrate	5,244,132
Total nitrogen fertilizer	57,807,019
Phosphate	19,309,058
Potash	3,338,697

Table 10. *Livestock numbers in the Yellowstone River Basin, 1987*

(Modified from Battaglin and Goolsby, 1994)

Type of livestock	Number raised
Cattle and calves	1,131,373
Beef cows	565,762
Steers, steer calves, bulls, and bull calves	266,136
Milk cows	6,846
Sheep and lambs	510,436
Horses and ponies	36,960
Hogs and pigs	35,810
Chickens (3 months or older)	20,583
Hens and pullets of laying age	14,182
Broilers and other meat-type chickens	4,459
Turkeys	1,247

Chemical pesticides often are applied to agricultural lands to control weeds, insects, and fungus. Applications to field crops are the dominant agricultural use of pesticides, followed by applications to pastures. Many of the chemical compounds applied are soluble in water and may be leached from the soil into surface or ground water.

The NAWQA program analyzed information on national and regional patterns of pesticide occurrence in surface water of the United States and the major influences on the sources and transport of pesticides (Larson and others, 1997). The following points are known in relation to surface water:

- Low levels of pesticides have been widespread in the Nation's surface water for several decades.
- Pesticide concentrations in surface water follow strong seasonal patterns that result from the timing of pesticide applications and runoff conditions.
- Many pesticides are rarely detected in surface waters because of relatively low use, how they are applied, chemical properties, or relatively insensitive analytical methods.
- In many streams, some pesticides exceed water-quality criteria for seasonal periods each year, but annual average concentrations seldom exceed regulatory standards for drinking water.
- Potential effects of pesticides on humans and aquatic ecosystems are difficult to evaluate because of inadequate information on effects of low-level mixtures, transformation products, and seasonal exposure.
- Improved information is needed on long-term trends, pesticides and transformation products that have not been widely measured, and biological effects of typical exposure patterns.

NAWQA also analyzed information on national and regional patterns of pesticide occurrence in ground water of the United States and the major influences on the sources and transport of pesticides (Barbash and Resek, 1996). The following points are known in relation to ground water:

- Pesticides from every major chemical class have been detected in ground water.
- Pesticides are commonly present in low concentrations in ground water beneath agricultural areas, but seldom exceed water-quality standards.
- Frequencies of pesticide detection are almost always low in low-use areas, but vary widely in areas of high use.
- Pesticide levels in ground water show pronounced seasonal variability in agricultural areas, with maximum values often following spring applications.
- Factors most strongly associated with increased likelihood of pesticide occurrence in wells are high pesticide use, high recharge by infiltration of either precipitation or irrigation, and shallow, inadequately sealed, or older wells.

NAWQA also analyzed information on national and regional patterns of pesticide occurrence in the atmosphere and the major influences on the sources and transport of pesticides (Majewski, 1995). The following points are known in relation to the atmosphere:

- Existing data, gleaned from 132 studies, are unevenly distributed, with most of the data from the Great Lakes region and California.
- Most of the pesticides studied have been detected in rain or air, but many that are used have never been studied.
- Pesticides have been detected in the atmosphere in all areas of the Nation sampled.
- Concentrations of a pesticide in air and rain are most affected by its use and resistance to environmental degradation.
- The highest atmospheric concentrations of pesticides occur seasonally in high-use areas when applications are greatest.
- Low levels of long-lived pesticides are present in the atmosphere throughout the year.
- Atmospheric deposition of pesticides is most likely to affect stream-water quality during runoff events when precipitation and direct surface runoff are the major sources of streamflow, but the full significance to water quality is largely unknown.

Within the study unit, the small area devoted to row crops (sugar beets, corn, and beans, primarily) is reflected by the types and amounts of herbicides that are most widely used in the YRB (table 11). The chlorinated phenoxy 2,4-D is used mainly as a postemergence herbicide on grassland, small grains, and fallow land (Meister, 1996). Dicamba is a benzoic acid used to control broadleaf weeds in asparagus, corn, grassland, fallow land, and small grains; picloram is used on broadleaf weeds in small grains and pastures, and for brush control on rangeland and utility rights-of-way; cycloate is a selective herbicide used for sugar beet production; EPTC is effective on grassy weeds and some broadleaf weeds in beans and potatoes; triallate is a selective herbicide for use in producing small grains and some beans and peas (Meister, 1996).

Table 11. *Estimated annual applications of the 12 most extensively used herbicides in the Yellowstone River Basin (Data from Battaglin and Goolsby, 1994)*

Pesticide	Estimated application of active ingredient, in kilograms
2,4-D	308,184
dicamba	127,223
picloram	76,611
cycloate	64,885
EPTC	60,017
triallate	57,883
MCPA	17,634
2,4-DB	14,526
diethatyl-ethyl[a]	10,189
alachlor	9,566
ethofumesate	7,152
cyanazine	6,156

[a]Discontinued by manufacturer in 1993.

The largest concentrations of pesticides detected in air and rain occur in those areas where they are used most frequently and in the largest quantities. Patterns of atmospheric pesticide concentrations from the early 1970s showed general correlations among atmospheric concentrations and regional use and cropping patterns (Majewski, 1995). Atmospheric pesticide concentrations within the YRB were low relative to areas of the Nation that have more intensive agricultural activity and more extensive cropland.

Urban Areas

Urban and residential areas affect surface- and ground-water quality by altering the physical hydrology and by adding waste products. Streamflow and ground-water flow are altered where rooftops, paved surfaces, and sewers accelerate the movement of storm runoff to streams at the expense of ground-water infiltration. Urban runoff frequently carries large nonpoint-source loads of sediment and inorganic and organic constituents from paved surfaces, parks, lawns, and golf courses. Point sources of contamination from the populated urban environment include sewage-treatment facilities, industrial discharges, landfills, and leaking storage tanks. Contamination of ground water by volatile organic compounds is a special concern because of its widespread occurrence in urban areas (Risser and Siwiec, 1996).

Urban or built-up land accounts for only 0.3 percent of the study unit area. However, in this small area there are a large number of point sources having the potential to contaminate receiving waters. The U.S. Environmental Protection Agency (USEPA) regulates 341 facilities in Billings, Montana. These facilities include National Pollutant Discharge Elimination System permit holders, hazardous waste handlers, Superfund sites, facilities releasing and transferring toxic chemicals, and sources of air pollution.

Herbicides, pesticides, and fertilizers are sometimes applied to urban land at greater rates than typically applied to agricultural land and can contribute to water-quality impairment. Lawns, gardens, parks, and golf courses are subject to intense pesticide applications. NAWQA determined that the most commonly detected insecticides in streams across the U.S. have substantial urban and suburban use (Larson and others, 1997).

Recent population growth in urban and suburban areas of the YRB represents potential water-quality problems. As sparsely populated grazing land is converted to residential use, there is increased risk of water supplies becoming contaminated. Many housing developments rely on septic systems from which contaminants can leach into the ground-water supply.

Minerals Extraction

In addition to agriculture and urban uses, other important land uses in the study unit include metals and coal mining and hydrocarbon production. These mineral industries are discussed in the following sections.

Metals Mining--The study unit contains few of the historically most productive metals mines in either Montana or Wyoming. However, there are some substantial deposits of metallic minerals within the YRB (fig. 9), and several areas experienced mining-related impacts. Potential water-quality problems associated with metals mining are increased sedimentation and the discharge of mine drainage that often exhibits water chemistry substantially different from the natural chemistry of the receiving water body. Mine dumps and tailings ponds are additional sources of potential concern. Surface-water quality could be affected by detention ponds used at uranium mines and tailings ponds at mills, but if operated properly, adverse effects are not likely (Lowry and others, 1993).

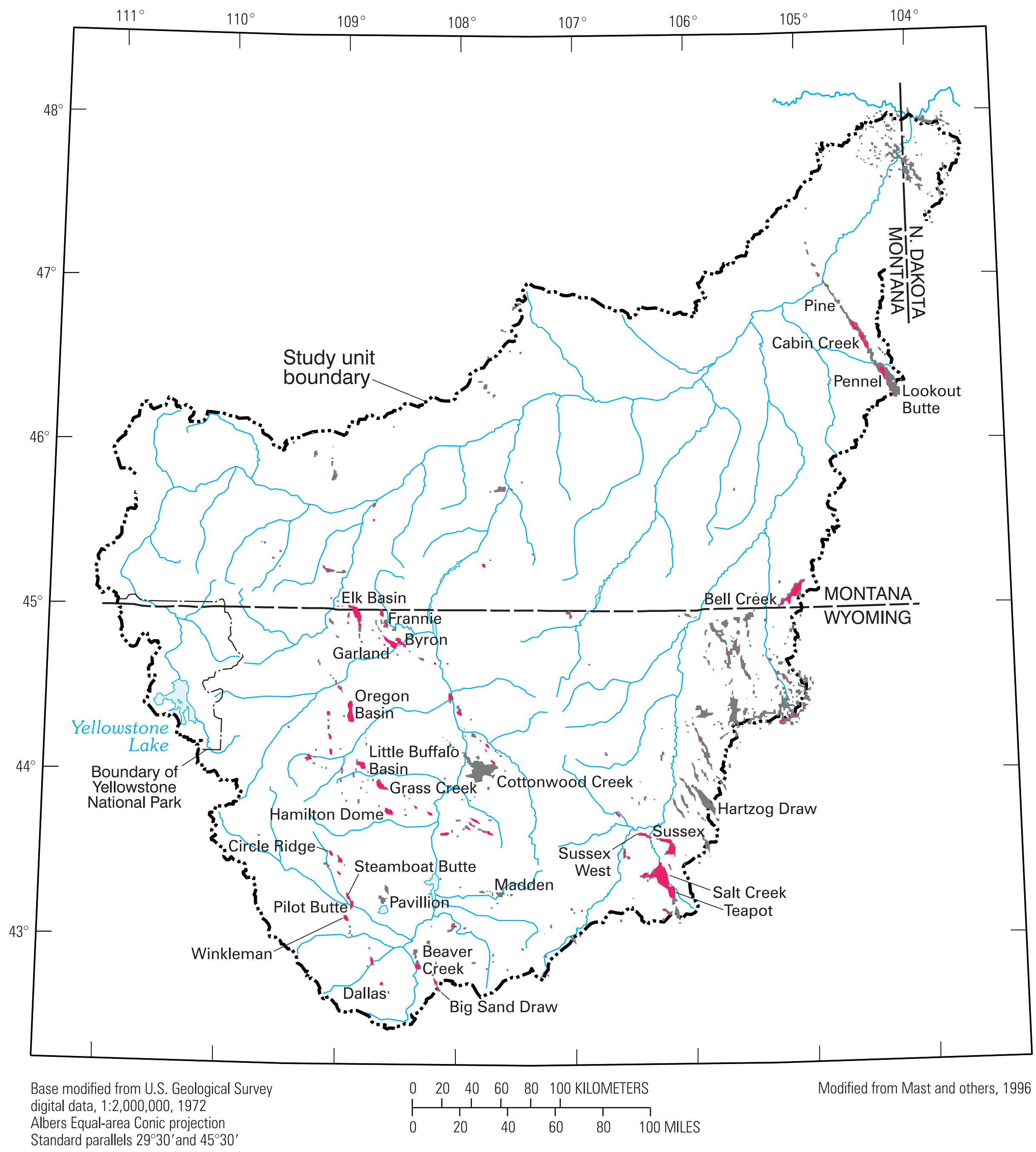
Metal deposits are known in some areas of the structural basins and at locations related to Cretaceous and Tertiary intrusions, but the Precambrian crystalline rocks have been the primary targets of prospectors and geologists seeking metallic ores. Early exploration for precious metals in the YRB led to the subsequent discovery of gold placer deposits in the vicinity of South Pass, Wyo. (fig. 9), in 1842, and in several tributaries of the upper Yellowstone River in the 1860s. However, lode deposits were not substantially developed until the 1860s near South Pass (Hausel, 1991) and in the 1870s at the Jardine and New World districts (fig. 9) of Montana (Hammarstrom and others, 1993a). Nickel, copper, and chromite deposits in the Precambrian Stillwater Complex (fig. 9) of Montana were discovered during 1883-90 (Hammarstrom and others, 1993a).

Historically, mines in the study unit have produced gold, silver, arsenic, tungsten, copper, lead, zinc, and chromium from lode deposits, as well as gold from placer deposits (Hammarstrom and others, 1993). But within the past 55 years, iron, chromium, uranium, and platinum have been the most important metallic mineral products of the YRB. The Atlantic City surface mine produced more than 80 million megagrams of iron ore from 1962 until operations ceased in 1983 (Hausel, 1984). (Although the Atlantic City mine pit lies just outside the study unit, part of the mine dump extends into the YRB [Hausel, 1991, plate 1], and is a potential influence on water quality in the study unit.) Some chromite was mined from the Stillwater Complex during and after World War II to provide government stockpiles of critical minerals (Hammarstrom and others, 1993), but large-scale chromite mining occurred during 1953-61 (Hammarstrom and others, 1993a). From the discovery of uranium in Tertiary sedimentary rocks in the early 1950s (Houston, 1979) until the rapid decline of the industry by the mid-1980s (Lowry and others, 1993), millions of megagrams of uranium ore were mined in the study unit. Development of the platinum-group elements (PGE) deposits of the Stillwater Complex began in the 1960s (Hammarstrom and others, 1993a).

In recent years, only four commercial mines have produced metallic ores in the study unit: (1) the Stillwater mine is producing PGE, gold, copper, and nickel from the Stillwater Complex (fig. 9); (2) the Mineral Hill mine had been producing gold and silver from lode deposits in the Jardine district (Hammarstrom and others, 1993) (fig. 9); (3) the Christiansen Ranch operation, an in-situ uranium producer located about midway between Casper and Gillette, is active (Harris, 1997); and, (4) a few kilometers north, the Irrigary uranium mine has become inactive recently (Anderson and others, 1993; R.E. Harris, Wyoming State Geological Survey, oral commun., 1998). The underground Stillwater mine recently expanded operations in order to increase the production goal to 1,800 megagrams per day. Closure of the Mineral Hill mine was recently announced (U.S. Geological Survey, 1997a). In the New World district, a proposed new project (underground mining of gold, silver, and copper) was on hold as Federal officials and environmental groups negotiated an exchange of private land holdings and unpatented mineral rights for surplus Federal property (U.S. Geological Survey, 1997a). In the Gas Hills, plans have been announced to construct a uranium mine and recovery plant (U.S. Geological Survey, 1997b).

Hydrocarbon Production--Located within the study unit are three of the largest oil fields of the Rocky Mountain region--the Salt Creek field in the Powder River Basin, and the Elk and Oregon Basins in the Bighorn Basin (fig. 20). Each field contained more than 500 million barrels of oil initially (Spencer, 1996). Two other YRB oil fields also rank among the top 120 nationally in annual production--Hartzog Draw in the Powder River Basin and Pennel in the Williston Basin (U.S. Department of Energy, Energy Information Administration, 1996). One of the Nation’s largest natural gas fields lies within the study unit--the Madden field in the Wind River Basin. In addition to the well fields, two large oil refineries at Billings, Mont., and a third located 27 km west, process almost 50 million barrels of crude oil annually (Montana Oil and Gas Conservation Division, 1996).

The importance of oil fields for understanding water-quality conditions and aquatic biota lies in potential contamination by both hydrocarbons and associated brines. Large volumes of saline water typically are produced in conjunction with oil extraction and commonly are discharged to nearby streams. Also, evaporation pits located in oil fields sometimes contain a surface layer of floating oil, which has been blamed for the deaths of numerous migratory waterfowl each year (Marsden, 1997). Pipeline breaks and accidental discharges are other events that can cause water-quality impairment.



EXPLANATION

Density of producing wells

Low to medium

Medium to high

Figure 20. Oil and gas fields, Yellowstone River Basin, Montana, North Dakota, and Wyoming.

Commercial oil production began in 1884 with the Dallas oil field in the Wind River Basin, and in 1889 at what later became the Salt Creek field (DeBruin, 1993). From 1906 through 1928, about 10 major fields within the YRB were discovered on anticlines along the margins of the Bighorn, Powder River, and Wind River Basins. Recent production estimates for several of the largest oil fields within each of the four major structural basins in the study unit are listed in table 12.

Hydrocarbon production in the Bighorn, Powder River, and Wind River Basins is predominantly from Cretaceous reservoirs and often is associated with structural features. About 90 billion m^3 of natural gas has been produced from Rocky Mountain foreland structures in those three basins, with 97 percent of hydrocarbon production in the Bighorn Basin having come from reservoirs in foreland structures (Mullen and Barlow & Haun, 1993). In the Bighorn Basin, most hydrocarbon production has come from anticlines around the basin margins, predominantly in association with oil reservoirs (Broadhead and Robertson, 1993). In contrast, the most productive reservoirs in the Powder River Basin have substantial stratigraphic components (Mullen and Barlow & Haun, 1993). Gas production in the Wind River Basin is predominantly from structural traps on basin margins and from stratigraphic and structural/stratigraphic traps near the basin center, from gas reservoirs not substantially associated with oil (Broadhead and Robertson, 1993). Nearly half of the 34 billion m^3 of structurally trapped gas produced in the Wind River Basin has come from the Beaver Creek field (fig. 20) near Riverton (Mullen and Barlow & Haun, 1993).

Foreland structures were primary targets for oil exploration through the 1950s, but early drilling in the Powder River Basin occurred near seeps that later were recognized as originating at stratigraphic traps (Mullen and Barlow & Haun, 1993). The large, shallow structural traps of the Bighorn Basin discovered prior to 1920 have produced more than half of its gas and three-fourths of the 2.2 billion barrels of oil produced through 1990 (Mullen and Barlow & Haun, 1993). In the Wind River Basin, many structural traps are related to basement block-fault adjustments and may have no surface expression (Mullen and Barlow & Haun, 1993).

The Frontier Formation of the Upper Cretaceous Series is the major hydrocarbon reservoir in the study unit. The nearshore marine sandstone of the Frontier Formation is particularly productive at the Salt Creek and Teapot fields north of Casper, Wyoming. From this 114 km^2 area, about 375 million barrels of oil and 21 billion m^3 of associated gas had been produced through 1990 using more than 2,000 wells (Doelger and others, 1993).

Contamination of streams or aquifers due to coal-bed methane development represents another hydrocarbon-related environmental concern (U.S. Geological Survey, Energy Resource Surveys Program, 1997). Partial pressure of the gas must be reduced to release it from the coal; this is achieved by removing water from the coal bed. The produced water is either discharged to the surface or injected underground. The salinity of the produced water is often greater than that of the receiving water body (U.S. Geological Survey, Energy Resource Surveys Program, 1997).

Coal Mining--In 1994, the United States produced 909 million megagrams and consumed 844 million megagrams of coal, with 88 percent used by electric utilities (U.S. Dept. of Energy, Energy Information Administration, 1995). About 30 percent (270 million megagrams) of the domestic coal production comes from beds in the Paleocene Fort Union Formation, which contains vast amounts of strippable coal (Flores, 1996), much of it located within the YRB. Production from the thick, sub-bituminous low-sulfur coal beds in the Powder River Basin is increasing rapidly in response to the demand for low-sulfur steam coal by electric utility consumers, primarily outside the YRB (U.S. Geological Survey, 1996b).

Coal was produced commercially in the YRB in the early 1880s near Red Lodge, Mont., in the 1890s in the Powder River Basin, and at several other locations by 1915-20 when early production peaked. Large-scale surface mining began in the 1920s from the Rosebud coal bed (fig. 21), but most of the YRB coal production prior to 1940 continued to be from underground mines (U.S. Department of Energy, Energy Information Administration, 1994). Another peak in coal production coincided with the war years of 1942-45, but most of the mines were closed prior to 1960 (Slagle and others, 1983; 1986). The present period of increased coal production began in 1962 with the opening of the Big Horn Mine (fig. 21) north of Sheridan, Wyo. (Slagle and others, 1983).

Table 12. *Principal oil fields in the Yellowstone River Basin (Data from Wyoming Oil and Gas Conservation Commission, 1997; and Montana Oil and Gas Conservation Division, 1996)*

[Montana data are for 1995; Wyoming data are for 1996]

Structural basin	Field	Year discovered	Annual oil production, 1995-96, in million barrels	Cumulative oil production through 1995-96, in million barrels
Bighorn	Elk Basin	1915	2.4	536
do.	Oregon Basin	1912	4.5	437
do.	Hamilton Dome	1918	1.8	248
do.	Grass Creek	1914	1.5	200
do.	Garland	1906	2.0	181
do.	Little Buffalo Basin	1914	.9	130
do.	Byron	1918	.7	126
do.	Frannie	1928	.3	116
do.	Cottonwood	1953	1.6	61
Powder River	Salt Creek	1889	2.4	653
do.	Bell Creek	1967	.1	132
do.	Hartzog Draw	1976	2.2	94
do.	Sussex-Sussex West	1948	.3	90
do.	Teapot	1922	.6	26
Williston	Pine	1952	.9	113
do.	Cabin Creek	1953	1.5	100
do.	Pennel	1955	2.3	91
do.	Lookout Butte	1961	1.0	29
Wind River	Winkleman	1917	.3	91
do.	Steamboat Butte	1943	.3	89
do.	Big Sand Draw	1918	.1	57
do.	Beaver Creek	1938	.3	57
do.	Circle Ridge	1923	.7	32

Since 1975 coal production from the study unit has increased dramatically, particularly in the Powder River Basin (U.S. Geological Survey, 1996b). The approximately ten-fold increase in production is due both to rising demand for fuel for electric power generation and to the unsuitability of coal from other regions for attaining environmental-quality goals. More than 25 percent of the Nation’s present coal production is from 25 mines developing the Wyodak-Anderson, Anderson-Dietz, and Rosebud coal beds or zones in the Powder River Basin (Flores, 1996). Some individual mines in the Powder River Basin produce more coal than some of the major coal-producing States to the east (Milici, 1996). All of the active coal mines in the study unit are surface (strip) mines. Despite tremendous current production, most fields in this coal region remain in early stages of development because transportation networks and markets remain less than fully developed (Milici, 1996; U.S. Geological Survey, 1996b).

More than 10 large surface coal mines are active, or temporarily idled, in the YRB: six of these strip coal from the Wyodak-Anderson bed in the mining area near Gillette, Wyo. (fig. 21), and another four

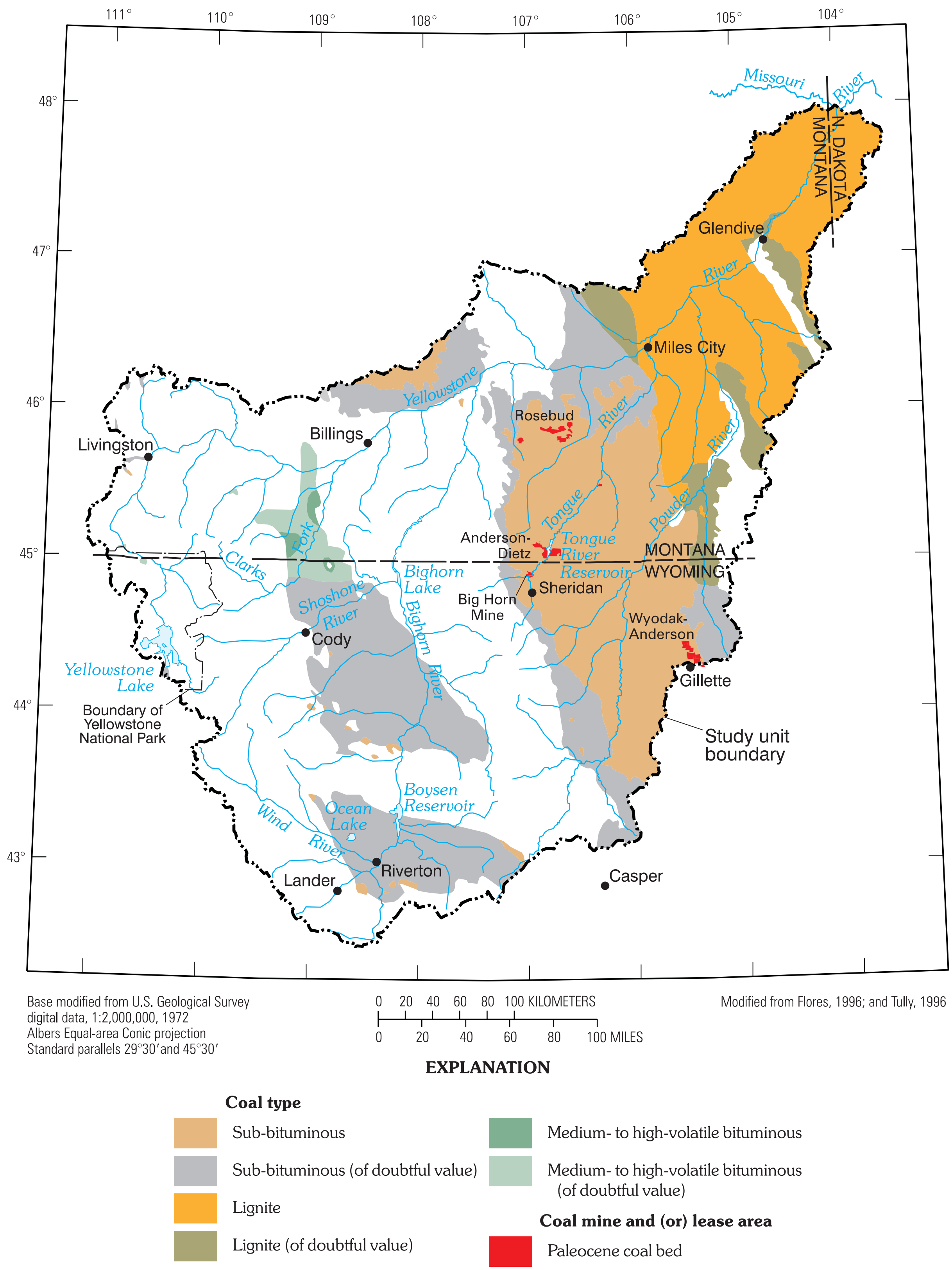


Figure 21. Coal types and major coal mine lease areas, Yellowstone River Basin, Montana, North Dakota, and Wyoming.

mine the Anderson-Dietz bed near or upstream of Tongue River Reservoir (Jones, 1990; Lowry and others, 1986; Slagle and others, 1983); four mines (fig. 21; not all active) developed in the Rosebud bed are located 40-50 km south of the Yellowstone River in Montana (Bergantino and others, 1980). The Wyodak-Anderson coal bed has an average thickness of 15-30 m with less than 15 m of overburden, and is the most important of several minable coal beds within the Tongue River Member of the Paleocene Fort Union Formation (Glass and Jones, 1991). The Anderson-Dietz coal bed is about 14 m thick north of Sheridan, Wyo. (Glass and Jones, 1991). The Rosebud coal bed is up to about 9 m thick with 6-15 m of overburden (U.S. Department of Energy, Energy Information Administration, 1994).

Although not yet extensively developed, a stratigraphically lower coal bed, the Knobloch, is about 23 m thick in a core area along the Tongue River valley about 50 km northeast from Tongue River Reservoir (Sholes and Daniel, 1992). At least one mine is actively strip-mining lignite beds about 45 km northeast of Glendive, Mont., but production is essentially negligible (U.S. Department of Energy, Energy Information Administration, 1994).

Surface mining may increase the potential for water-quality problems. Surface mining alters the configuration of the land surface and subsurface strata, and long-term detrimental effects may result if the area is not properly reclaimed. Mining operations, which include vegetation removal, excavation, and production of large volumes of unconsolidated spoil material, increase the potential for erosion and sedimentation. Channel filling by sedimentation can decrease the water-carrying capacity of the stream and may lead to increased flooding. The habitat of aquatic organisms may be altered substantially through burial and decreased dissolved-oxygen concentration of the water, owing to decreased depth and increased temperature. Dissolution of minerals contained in sediment derived from recently excavated overburden material may result in increased dissolved-solids and trace-element concentrations and decreased pH values.

Acid mine drainage from coal beds is virtually unknown in the Northern Great Plains and Rocky Mountain Provinces. Coal in these provinces has fewer sulfide minerals, and the semiarid climate results in less water to transport the acid, should it form. In addition, the natural alkalinity of water and soil in the Western United States generally neutralizes acid, should it form.

Erosion and sediment deposition, potential issues in any watershed affected by mining, generally are controlled at all active mine sites as required by State and Federal surface-mining regulations. Erosion is controlled by proper grading and revegetation of areas affected by mining, and sediment runoff is controlled through the use of settling ponds. However, channel scour can modify aquatic habitat downstream from settling ponds if the discharged water has suspended-sediment concentrations that are substantially smaller than the natural, or premining concentrations (Britton and others, 1989).

The potential effects of mining on ground water have caused some concern. Regionally, however, there probably will be no measurable effect on the quantity of flow because flow is dominantly local, rather than regional, in the upper several hundred feet of the coal-bearing rocks. The possible effects on quality of water have not been fully assessed (Lowry and others, 1986), although results from geochemical modeling in the Powder River Basin indicate potential for improved postmining water quality (Martin and others, 1988).

> "Ground-water levels may be affected by surface coal mining. Mines located above water-yielding zones have little, if any, effect on water levels. Ground-water levels can decline in and near surface-mined areas where excavation intersects a water-yielding zone. Water-level declines may cause a decrease or loss of production or flow in wells and springs. These effects generally will be temporary and occur only during and for a limited time after active mining. The areal extent of mining effects on water levels is largely dependent on the geologic and hydrologic setting of the mine and the duration of mine dewatering. Coal beds are characterized by fracture systems that provide limited paths for the movement of water. Consequently, each sand lens or fracture system not contiguous with another can be considered to be an individual and relatively isolated aquifer. Recharge available to this individual aquifer is limited to leakage through the surrounding confining layers; thus, the areal extent of water-level changes resulting from mining can be relatively local. In most instances, upon completion of mining, water levels will rise until premining equilibrium conditions are approximated" (Slagle and others, 1984, p. 22).

The quality of ground water in the vicinity of surface mines may be affected by the replacement of overburden material after the coal is removed. Replacement of overburden results in the exposure of fresh mineral surfaces and provides the opportunity for renewed chemical reactions. The actions of sulfate-reducing bacteria can decrease sulfate concentrations. Chemical analyses of spoil-derived water from the Powder River Basin (Rahn, 1975; Van Voast and others, 1978) have indicated that the median dissolved-solids concentration of water in spoils can be 160 to 173 percent of that in stock and domestic wells. Computer modeling designed to assess potential increases in dissolved solids in streams as a result of leaching of spoil materials (Woods, 1981) indicates that large increases in dissolved-solids concentration are local and dilution occurs downstream. Simulation of a hypothetical plan to simultaneously mine all Federally owned coal potentially available for mining in the Montana part of the Tongue River Basin resulted in a maximum increase of 4.7 percent in the average annual dissolved-solids concentration of the Tongue River at Miles City.

Cooperative and individual studies of effects of existing mines by the Montana Bureau of Mines and Geology and U.S. Geological Survey (1978) have shown that:

- Ground-water inflow to mine pits generally has been small.
- Mine effluents have not created serious water-quality problems.
- Local water-level declines can be substantial during mining.
- Water levels generally will recover toward premining positions after mining ceases.
- Mine spoils generally transmit water as well as or better than the natural aquifers.
- The problem of mineralization of water is small regionally.
- Deeper aquifers are available to replace water supplies that are permanently lost.

> “The largest impact on the hydrology probably will be caused by the increases in population and land use, rather than actual mining activities” (Lowry and others, 1986, p. 6).

Water Use

An awareness of how water is used in the YRB is necessary to understand hydrologic conditions. In general, water use refers to a set of interactions between human activities and the hydrologic environment. Within the YRB, agriculture, mining, thermoelectric power generation, other industries, municipal and domestic supply are the chief purposes for which water is withdrawn, delivered, and consumed or returned.

Withdrawals are quantities of water removed from ground- or surface-water sources and are considered to be self supplied. Delivery is water withdrawn from a ground- or surface-water source by a municipal water supply and conveyed to customers. Consumptive use is water evaporated, transpired, combined into products or crops, or consumed by humans or livestock and not immediately available for reuse. Water that reaches a ground- or surface- water source after leaving the point of use is considered a return (Solley and others, 1993). Return flows commonly affect the temperature and suspended-solids, nutrient, and major-ion concentrations of the receiving water body.

About 98 percent of all water used in the study unit in 1990 was surface water (table 13). Most of this water—about 99 percent—was used for agricultural crop and livestock production. However, ground water is an important resource in the study unit. About 97 percent of the domestic supply and about 27 percent of the public supply is from ground water. About 61 percent of the ground-water use in 1990 was for agricultural purposes. Mining, power generation, and industry made up most of the remaining uses of surface and ground water in 1990 (fig. 22).

Recreational uses, although important, are difficult to quantify. Many streams and lakes are heavily used for recreation, and the demand is increasing—affecting the water quality and aquatic organisms. The cold-water fisheries program stocked several million trout. Most of these were placed into high-quality cold-water streams.

There are no storage reservoirs on the mainstem of the Yellowstone River, though a proposal to build one at the narrows, just south of Livingston, was defeated in the 1970s (Chapple, 1997). However, hundreds of small impoundments for water supply, recreation, power, and flood control have been constructed within the study unit, in addition to several large dams on the major tributaries to the Yellowstone River. The six largest storage reservoirs in the study unit are listed in table 14.

Table 13. *Reported surface- and ground-water use by category, 1990, Yellowstone River Basin*

(Modified from Miller and Quinn, 1997)

[m^3/d, cubic meters per day; Mgal/d, million gallons per day]

Category	Surface-water use		Ground-water use	
	m^3/d	Mgal/d	m^3/d	Mgal/d
Public supply	150,000	40	57,000	15
Domestic (self-supplied)	800	.21	24,000	6.3
Commercial	680	.18	950	.25
Industrial	61,000	16	5,700	1.5
Thermoelectric power	120,000	33	0	0
Mining	34,000	9.0	140,000	37
Agriculture	26,000,000	6,900	350,000	93
[a]Total	26,000,000	7,000	570,000	150

[a]Values expressed using two significant figures.

Reservoirs often have a dramatic effect on water quality and resident biota. The typically nutrient-rich, stilled water allows aquatic vegetation to flourish, which can greatly diminish dissolved-oxygen concentrations through respiration and decomposition (Cole, 1983). Reservoir construction causes a loss of riparian habitat through inundation, and alters the aquatic and riparian habitats downstream (Knight, 1994). Reservoirs can be very effective sediment traps; flowing water loses its transport capacity as it enters a calm water body and deposits its sediment load. In addition, reservoir water levels typically fluctuate considerably—high in the late spring to store snowmelt runoff for flood control and for the onset of the agricultural irrigation season, but low by the end of the growing season. Fluctuating water levels create nearly barren shores around such reservoirs when the water level is low, because most riparian plants cannot tolerate the drastic fluctuations of water levels (Knight, 1994).

Waste Disposal

Waste materials deposited into water, land, air, and underground disposal sites can become a source of surface- and ground-water contamination. Although substantial improvements have been made in recent years in their disposal, wastes have not always been properly handled. Hundreds of active or abandoned waste sites exist in the YRB, including two sites from the USEPA's Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) National Priorities List.

The USEPA's Toxics Release Inventory (TRI) is a publicly available database containing specific toxic-chemical release and transfer information from industrial facilities (table 15). Facilities that have the equivalent of 10 or more full-time employees and meet the established thresholds for manufacturing, processing, or otherwise using listed chemicals must report their releases and transfers. The TRI does not account for toxic emissions from automobiles and many other non-industrial sources.

Disposal to Streams

Sewage and industrial wastes can cause problems associated with bacteria, nutrients, dissolved oxygen, suspended solids, organic compounds, and trace elements in streams. Many bacteria are pathogens. Nutrients, such as nitrogen and phosphorus, can stimulate growth of aquatic plants and contribute to algal blooms. An algal bloom is the rapid growth of one or more species of suspended (phytoplankton) or attached (periphyton) algae that leads to an accumulation of algal biomass. As the algae die, decomposition can consume more oxygen than the living algae produce; hence, the dissolved-oxygen concentration of the water can decrease below the level needed for fish to survive. Suspended solids decrease light penetration, can be harmful to fish in large concentrations, and, if deposited, decrease the water-carrying capacity of the stream and may lead to increased flooding. Organic compounds and trace elements are ubiquitous contaminants having the potential to bioaccumulate in living organisms.

The Federal Water Pollution Control Act of 1972 (commonly known as the Clean Water Act) requires wastewater dischargers to have a permit establishing pollution limits, and specifying monitoring and reporting requirements. National Pollutant Discharge Elimination System (NPDES) permits regulate household and industrial wastes that are collected in sewers and treated at municipal wastewater treatment plants. Permits also regulate industrial point sources and concentrated animal feeding operations that discharge into other wastewater collection systems, or that discharge directly into receiving water bodies. More than 200,000 sources are regulated by NPDES permits nationwide.

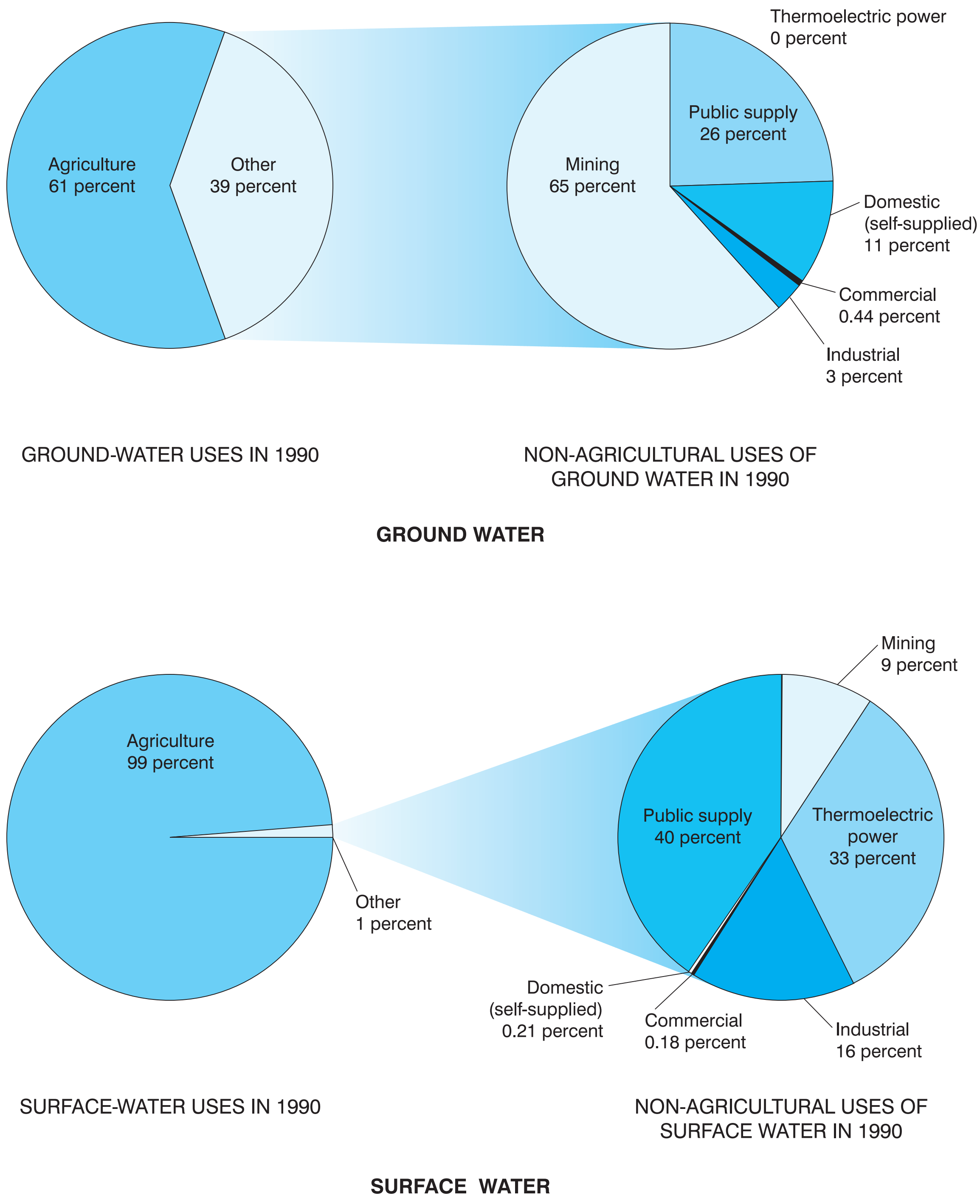


Figure 22. Estimated water use, 1990, Yellowstone River Basin.

Table 14. *Names and descriptions of major reservoirs in the Yellowstone River Basin*

(Data from Brosz and Hasfurther, 1990; Harza Engineering and others, 1983; Shields and others, 1997)

[km, kilometer; km^3, cubic kilometer]

Reservoir name (fig. 1)	Year completed	Storage capacity, in km^3 (acre-feet)
Bull Lake[a]	1938	.189 (153,000)
Boysen Reservoir	1951	.989 (802,000)
Buffalo Bill Reservoir[b]	[c]1909	.857 (695,300)
Bighorn Lake	1967	1.695 (1,375,000)
Tongue River Reservoir	1939	.084 (68,040)
Lake De Smet[d]	[e]1921	.290 (235,000)

[a]Not shown in fig. 1; located 58 km west-northwest of Riverton, Wyo.

[b]Not shown in fig. 1; located 11 km west of Cody, Wyo.

[c]Dam height increased by 7.6 meters, effective 1992; previous storage capacity was 0.746 km^3 (424,000 acre-feet)

[d]Not shown in fig. 1; located 39 km south-southeast of Sheridan, Wyo.

[e]Dams enlarging the storage capacity of this natural lake were completed in 1921, 1971, and 1978.

Table 15. *Toxic Release Inventory emissions in the Yellowstone River Basin, 1993*

(Data from U.S. Environmental Protection Agency, 1995)

[All values in thousands of kilograms]

Industry type	Water	Land	Air	Under-ground	Total
Petroleum refineries	51	0.8	266	0	317
Chemical manufacturing	0	0	20	0	20
Mining and extraction	0	0	0.2	0	0.2
Other manufacturing	27	12.6	245	0	285
Total[a]	78	13.4	531	0	622

[a]Values expressed using three significant figures.

One-hundred thirty-two NPDES permitted facilities were listed in the YRB in 1997. Of these, 26 facilities are identified as major dischargers (12 municipalities, 4 beet-sugar manufacturers, 4 mines, 3 petroleum refineries, 2 electric power-generating plants, and 1 railroad yard).

The USEPA's TRI database listed about 78,000 kg of toxic releases to water in 1993 from manufacturing facilities in the YRB. About 65 percent of this total is attributable to petroleum refineries, with the remainder resulting from other manufacturing operations.

Disposal on Land

Wastes are disposed on land within the YRB by several methods including septic systems, landfills, surface impoundments, and land application of treated substances. These methods generally have a more immediate potential to contaminate shallow ground-water resources than to affect stream water.

Septic systems contribute filtered sewage effluent directly into the ground. The septic effluent contains bacteria, nutrients, organic carbon, chlorides, and contaminants from household wastes. Septic systems are designed to use the soil to filter bacteria and attenuate as many of the other constituents as possible. However, where soil is thin, or where permeable rocks underlie the septic system, ground-water contamination is likely. A cesspool pit can pose a serious contamination threat to the nearby well-water supply (Risser and Siwiec, 1996). As ranch land is converted to rural residential use there is a greater risk of contamination of the water supply.

The USEPA's TRI database listed about 13,400 kg of toxic releases to land in 1993 from industrial facilities in the YRB. It is estimated that 90 percent of the industrial wastes that are considered to be hazardous are landfilled, primarily because it is the least expensive waste management option (Freeze and Cherry, 1979). The USEPA's Office of Solid Waste listed 41 active municipal solid-waste landfills in the YRB in 1995 (U.S. Environmental Protection Agency, 1996b). At a landfill, solid waste is reduced in volume by compaction and then is covered with earth. In North America a large number of the older sites that receive municipal wastes are open dumps or poorly operated landfills. Newer sites are generally better situated and better operated. Nevertheless, contamination of surface and ground water from landfills is possible from storm runoff and infiltration of leachate. Not only do the leachates contain contaminants derived from the solids, but many leachates contain toxic constituents from liquid industrial wastes placed in the landfill.

Surface impoundments are used primarily to store wastes. Surface- and ground-water contamination can result if the impoundment leaks. Nutrient contamination—nitrates in particular—of ground water is a concern arising from the storage of animal manure.

Land application is widely used to dispose of stabilized municipal sewage sludge, septic-tank wastes, sludge from drinking-water treatment plants, and composted leaves. Treated wastes are commonly applied directly to the land surface in the study unit. This disposal method employs natural properties of soil and biota to remove bacteria and excess nutrients in the waste (Metcalf and Eddy, Inc., 1972). Care, however, must be exercised to assure that the ability of the soil to assimilate wastes is not overloaded; otherwise, groundwater contamination will result.

Disposal in Air

In the Western United States, available data indicate that precipitation at individual sites has been acidified by anthropogenic emissions. The acidification generally has been attributable to localized sources and the time of initial acidification is undefined (Turk, 1983).

The USEPA's TRI database listed 531,250 kg of toxic releases to the air from industrial facilities in the YRB in 1993. About 50 percent of this total is attributable to petroleum refineries and another 46 percent resulted from other manufacturing operations. These amounts do not include small generators and non-point sources such as automobiles and agricultural-chemical applicators. Total emissions would likely be much greater if these other sources were included.

Precipitation cleans the atmosphere of airborne toxic vapors and particles and deposits them onto the earth's surface, including lakes, rivers, and streams. In addition, dry atmospheric deposition in the form of vapors and particulate matter also returns airborne compounds to the earth's surface. Toxic compounds in both precipitation and dry deposition reach surface water as direct deposition and in surface runoff, and can reach ground water by infiltration through the soil (Majewski, 1995).

Disposal Underground

Injection of liquid wastes, mainly of industrial origin, has been widely adopted as a waste disposal practice in North America (Freeze and Cherry, 1979). The purpose of this procedure is to isolate hazardous substances from the biosphere. As the discharge of pollutants to rivers and lakes has become increasingly objectionable, and as legislation for protection of surface water resources has become more stringent, the use of deep permeable zones for liquid waste disposal has become an increasingly attractive waste management option for many industries. Chemical, petrochemical, and pharmaceutical companies are the largest users of waste-injection wells. Other important users are petroleum refineries, gas plants, steel mills, potash mines, uranium mills, and processing plants (Freeze and Cherry, 1979). Large septic systems used for disposal of sanitary waste in establishments serving more than 20 people per day, or any septic system used for industrial wastewater, qualify as “underground injection wells” regulated by USEPA's Underground Injection Control program. The Wyoming Department of Environmental Quality lists several hundred sites of underground injection in the YRB (Bob Lucht, Wyoming Department of Environmental Quality, oral commun., 1998).

Integrated Environmental Settings

Several sources of information are available that show the geographic distribution of environmental settings at national or continental scales as analyzed by previous investigators. Such settings integrate many interrelated characteristics, such as climatic, physiographic, geologic, biotic, and land-use features. One of the benefits of developing a regional framework of environmental settings is its use in selecting regional reference sites (Gallant and others, 1989). Such sites are used within the NAWQA Program to represent unimpaired or relatively unimpaired water-quality conditions for a specific environmental setting. Water-quality data collected from impaired sites can then be compared with those from environmentally similar reference sites.

Ecoregions

Ecosystems of regional extent, also known as ecoregions, have been defined and mapped by a number of investigators. Two of the more widely used classification systems for ecoregions of the U.S. are those developed by R.G. Bailey and J.M. Omernik.

Bailey's ecoregions (1:7,500,000 scale) (Bailey and others, 1994) are based on associations of environmental factors that directly affect or indirectly express energy, moisture, and nutrient gradients that control the structure and function of ecosystems; these factors include climate, landforms, vegetation, and soil (Bailey, 1996). In Bailey's hierarchical system, developed to support ecosystem management on land administered by the U.S. Forest Service, the YRB lies in the dry climate domain, a subcontinental region of broad climatic similarity. Within the dry domain, several divisions are defined by vegetation differences corresponding to the levels of water deficit and winter temperatures (Bailey, 1995). Two of these divisions occur in the YRB. Eighty-two percent of the study unit is classified as temperate steppes, areas having shortgrass prairie or semidesert vegetation that is generally sparse, leaving much exposed soil (Bailey, 1995). Bailey maps the remainder of the YRB as temperate deserts, where vegetation is typically semidesert shrubs such as sagebrush.

Bailey's delineation places 53 percent of the study unit in the Great Plains Dry Steppe Province, characterized by grasslands with scattered trees and shrubs. Another 29 percent of the YRB lies in the Southern and Middle Rocky Mountain Steppe Provinces where local vegetation zones are controlled by a combination of altitude, latitude, prevailing winds, and slope exposure (Bailey, 1995). The Intermountain Semidesert Province occupies about 18 percent of the study unit and features sagebrush mixed with short grasses. On moist, alkaline soils, greasewood is an abundant shrub.

At the same scale of 1:7,500,000, Omernik (1987) mapped the principal ecoregions of the U.S. based on integrated patterns of a combination of factors including land use, morphology, potential natural vegetation, and soil. Omernik's map was developed specifically in support of water-resources management and is based on the premise that regional patterns of these environmental factors would be reflected in water-quality patterns (Gallant and others, 1989). Planned applications for the ecoregion maps include development of regional biological criteria and water-quality standards, and establishment of management goals for nonpoint-source water pollution (U.S. Environmental Protection Agency, 1996a).

The authors have attempted to refine the current version of Omernik's ecoregions (U.S. Environmental Protection Agency, 1996a) within the YRB to more closely follow changes in land cover and geology seen on larger-scale sources of map data. Additional rationale for modification to the national-scale ecoregion map is found in the results from an adjacent NAWQA study unit, where patterns in fish-species distributions and assemblages did not correspond well with those ecoregion boundaries (Maret and others, 1997). On our modified map of Omernik's ecoregions (fig. 23), 55 percent of the study unit lies within the Northwestern Great Plains. This ecoregion has plains with open hills of varying height and tablelands of moderate relief; and predominant land cover is subhumid grasses used for grazing (Omernik, 1987). Twenty-one percent of the YRB lies in each of two other ecoregions, the Middle Rocky Mountains and the Wyoming Basin. The Middle Rocky Mountains ecoregion features high mountains covered by Douglas fir, western spruce-fir forests, and alpine meadows (Omernik, 1987); land use includes grazing and silviculture. The Wyoming Basin has plains with hills or low mountains, some irrigated agriculture, and potential natural vegetation is shrub steppe, desert shrubland, and juniper-pinyon woodland (Omernik, 1987). The remainder of the YRB lies in the Montana Valley and Foothill Prairies ecoregion, characterized as subhumid grassland used for grazing, and some irrigated land (Omernik, 1987).

Environmental Stratification

Natural and anthropogenic factors, such as geology and land use, provide a framework for making comparative assessments of water quality within and among hydrologic systems at a range of scales and in different parts of the Nation (Gilliom and others, 1995). Characterizing this environmental framework is an important element in each study-unit investigation of the NAWQA Program. The environmental setting of a study unit is characterized by dividing it into several subareas (not necessarily contiguous) that have relatively homogeneous combinations of those natural and anthropogenic factors believed to be relevant to water quality (Gilliom and others, 1995). In terms of a design for a scientific study, this process is called stratification.

Six environmental data layers were included in a digital map overlay analysis to identify relatively homogeneous subareas for use in designing the YRB study-unit investigation. Three of the data layers have complete geographic coverage for the YRB: ecoregions, geologic units, and land cover or land use. The other three data layers are composed of localized areas where mineral deposits and (or) extraction activities occur or have a substantial likelihood of occurring: coal lease areas, metallic mineral deposits, and oil fields.

A three-tiered approach was used to stratify the study unit on the basis of environmental settings. Ecoregions represent an integration of multiple environmental controls and were distinguished by Omernik (1987) partly based on expected influence on water quality. Therefore, the four ecoregions (fig. 23) were selected as the first tier for the environmental stratification process.

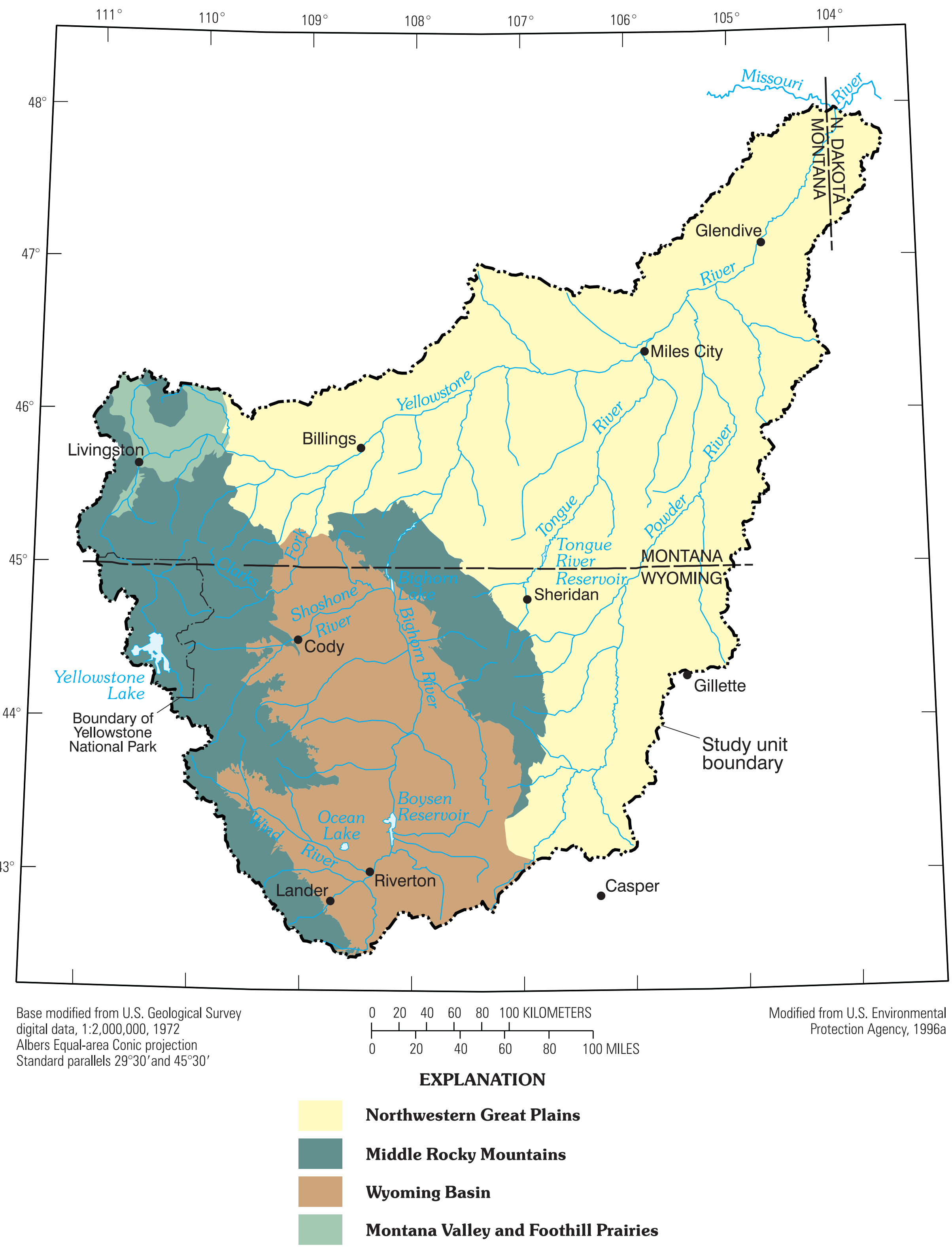


Figure 23. Ecoregions, Yellowstone River Basin, Montana, North Dakota, and Wyoming.

Geologic groups were selected as the second tier. The areas where mineral deposits and (or) extraction activities occur or may be likely were combined to form one geologic group, called mineral resource areas. The remainder of the study unit was assigned to geologic groups on the basis of generalized geologic units (fig. 6). Igneous rocks were grouped into Precambrian crystalline rocks and Cretaceous through Quaternary volcanic and intrusive rocks. The crystalline rocks crop out mainly at the core of three of the mountain uplifts in the YRB and typically produce water-quality characteristics distinct from either volcanic or sedimentary rocks (see *Water-Quality Characteristics* section of report). Sedimentary rocks were grouped into a “Paleozoics” group that also includes Mesozoic strata (Jurassic and Triassic rocks), a Cretaceous group, and a Tertiary group. Paleozoic units include numerous carbonate strata that exert a substantial influence on both water chemistry and hydrology. Water in Cretaceous aquifers typically contains considerably larger concentrations of dissolved solids than do many Tertiary aquifers. The areas of Quaternary unconsolidated deposits were assigned to the nearest neighboring geologic unit, and grouped accordingly.

For the third tier, land cover and land use, the categories used are those designated as Level I categories in the Anderson (1976) classification system. These major groupings of land cover and land use are associated with different, though generalized, expected impacts on water-quality characteristics.

The results of the digital map overlay analysis were a large number of types of relatively homogeneous areas—many more than could be considered as separate environmental settings for the study design. Therefore, selected types of relatively homogeneous areas were designated as environmental settings. Selections were made first based on NAWQA Program priorities, and then based on relative areal extent within the study unit.

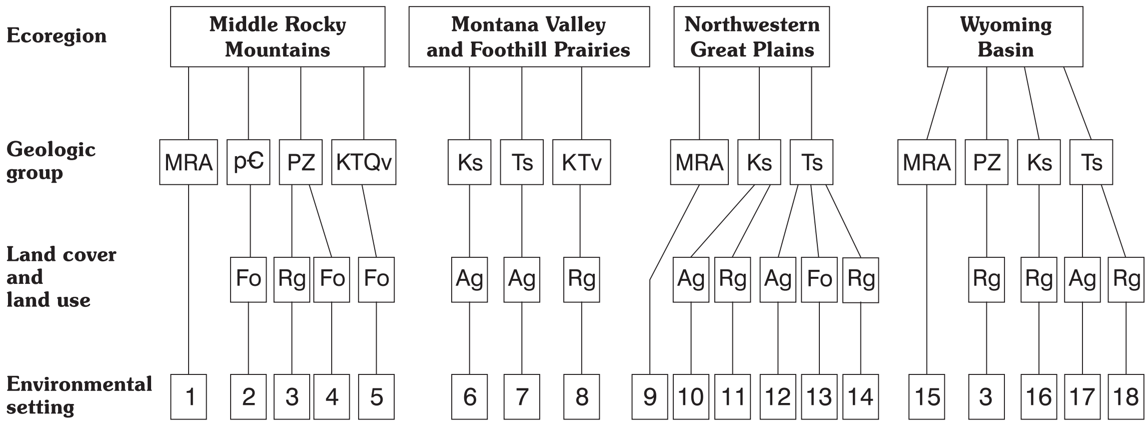
Specific environmental settings have been prioritized by the NAWQA Program for sampling by study-unit investigations, such as urban, agricultural, and mining areas. However, NAWQA is targeting large urban areas that have populations greater than 250,000 (Lopes and Price, 1997). In the YRB, no urban areas are large enough to qualify as targets for study. Mineral resource areas were given priority. The environmental factor combinations of mineral resource areas that were most areally extensive were selected as environmental settings, whereas less extensive factor combinations were left unassigned to any setting. For example, 91 percent of the metallic mineral deposits were located in five types of relatively homogeneous areas occurring in three ecoregions; consequently, those five types of relatively homogeneous areas were assigned to an environmental setting according to ecoregion, but the other 9 percent of the metallic mineral deposits were left unassigned. Areas of coal and oil resources were prioritized similarly.

After the higher priority environmental-setting assignments had been made, areal extent was used to rank the remaining combinations of environmental factors. Generally, factor combinations that covered at least 1.5 percent of the study unit were assigned to environmental settings. The notable exception to this generalization is that alpine tundra areas were not assigned to any setting even though two combinations (combinations of tundra with the Precambrian and volcanic geologic groups) do cover about 1.5 percent of the study unit. Alpine tundra areas do not carry sufficient priority within the NAWQA Program to warrant specific consideration for study.

A total of 18 environmental settings (fig. 24 A) were thus defined for the YRB. Relatively homogeneous areas from different ecoregions were not assigned to the same environmental setting, except in one case. Rangeland underlain by the Paleozoic geologic group in both the Middle Rocky Mountains and Wyoming Basin ecoregions were assigned to the same environmental setting because this geologic group mainly occurs in the transitional areas along the boundary between these two ecoregions.

In figure 24 B, colors applied to environmental settings are unique within each ecoregion, but the same color is sometimes used for similar environmental settings located in different ecoregions. About 11 percent of the study unit is composed of environmental-factor combinations that were not assigned to any environmental setting. If this initial environmental stratification of the study unit is adopted in the final study design, those combinations will not be targeted for specific study, though some of those areas will unavoidably be included within watersheds or aquifer areas that will be selected for study. The 18 environmental settings are considered initial candidates for specific study components, but resource constraints will not allow all 18 settings to be studied during the current phase of the YRB study-unit investigation. However, the spatial heterogeneity of selected study areas with respect to the included environmental factors will be

A



EXPLANATION

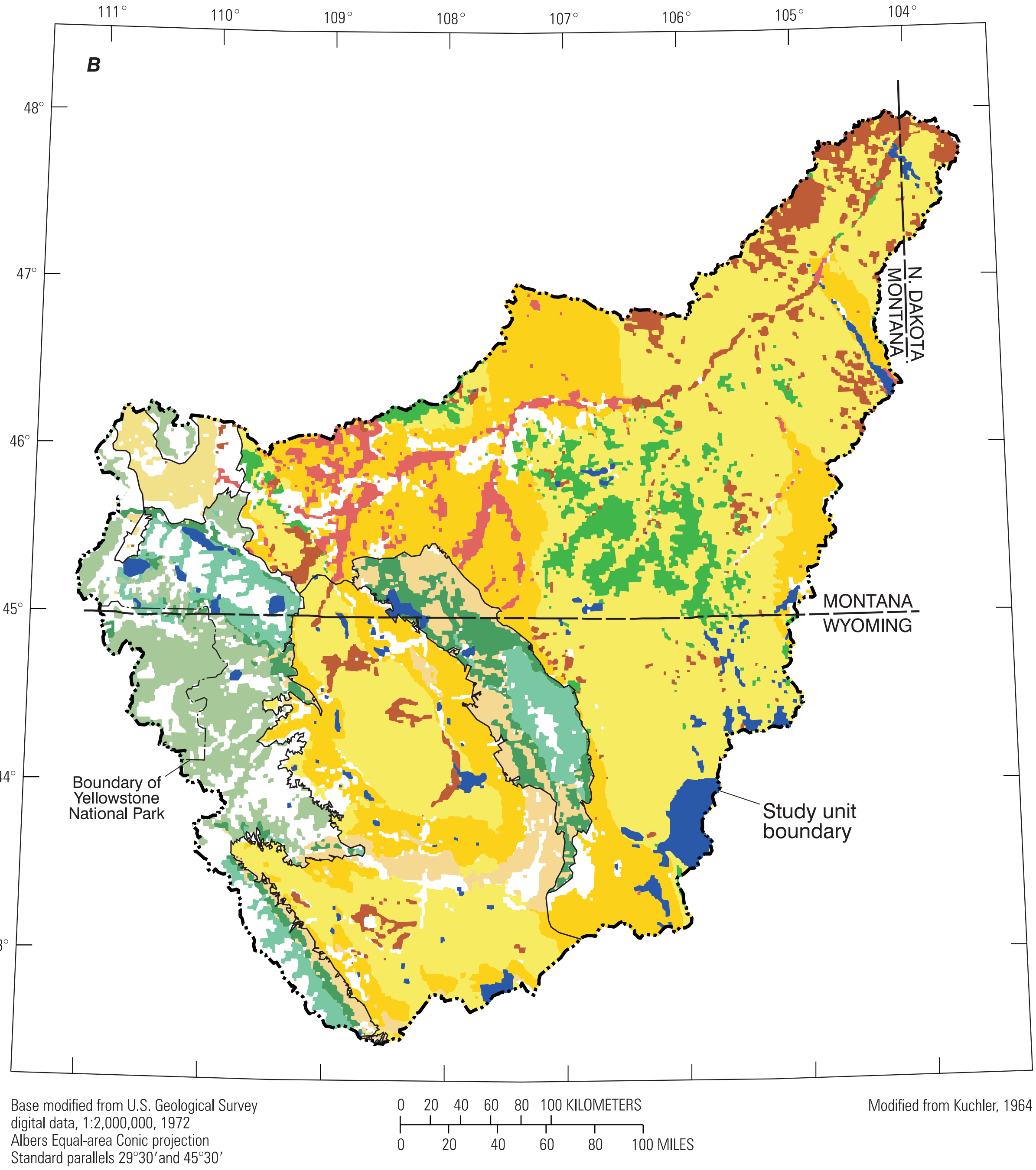
Geologic group

MRA — Mineral resource area
Ts — Tertiary sedimentary rocks
KTv — Tertiary and Cretaceous volcanic rocks
KTQv — Cretaceous, Tertiary, and Quaternary volcanic rocks
Ks — Cretaceous sedimentary rocks
PZ — Paleozoic and Mesozoic sedimentary rocks
p€ — Precambrian crystalline rocks

Land cover and land use

Ag — Agricultural
Fo — Forest
Rg — Range

Figure 24. ***A***, Schematic diagram, and ***B***, map of environmental settings of Yellowstone River Basin.



EXPLANATION

——— **Ecoregion boundary**

Environmental settings (and percentage of study unit)

1 (0.6)	6 (0.05)	11 (13.0)	16 (5.8)
2 (3.4)	7 (0.06)	12 (4.9)	17 (0.9)
3 (4.8)	8 (1.2)	13 (4.4)	18 (9.8)
4 (3.0)	9 (2.0)	14 (25.7)	Not assigned (11.2)
5 (5.4)	10 (3.0)	15 (0.6)	

Figure 24. Continued.

readily quantified using the results from the stratification analysis. The selected factors were included because of their perceived influence on water quality or aquatic ecology, so differences in these conditions measured during the study-unit investigation are expected to correspond to differences in environmental setting.

SUMMARY

This report describes the natural and anthropogenic factors believed to influence water-quality conditions in the Yellowstone River Basin (YRB). Major water-quality issues in the YRB are sediment, trace elements, toxic compounds, salinity, and stream-habitat degradation. Land and water uses that relate to these issues include grazing, agriculture, mining, oil production, and residential expansion into rural areas.

The physiography parallels the structural geologic setting that is generally composed of several uplifts and structural basins. Contrasts in climate and vegetation reflect topographic controls and the midcontinental location of the study unit. Surface-water hydrology reflects water surpluses in mountainous areas dominated by snowmelt runoff, and water deficits in the remainder of the study unit. Principal groundwater aquifers are Tertiary sandstones and unconsolidated Quaternary deposits.

Human population, though sparsely distributed in general, is growing most rapidly in a few urban centers and resort areas, mostly in the northwestern part of the YRB. Land use is areally dominated by grazing in the basins, and economically dominated by mineral-extraction activities. Forests are the dominant land cover in mountainous areas. Cropland is a major land use in principal stream valleys. Water use is dominated by agriculture overall, but mining and public-supply facilities are major users of ground water. Coal and hydrocarbon production and reserves distinguish the YRB as a principal energy-minerals resources region. Current metallic-ore production or reserves are nationally significant for platinum-group elements and chromium.

Other investigators integrated multiple environmental factors to subdivide the YRB into ecological regions that serve as a starting point for an initial environmental stratification of the study unit. Ecoregions, geologic groups, and general land-cover and land-use categories were used in combination to define 18 environmental settings in the YRB that collectively describe about 89 percent of the study unit. These 18 settings are initial candidates for targeted study components that will be used to assess and compare water-quality conditions.

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GLOSSARY

Allochthonous refers to materials, such as organic sediments, that originate outside a given ecosystem and thus provide external inputs of food energy or nutrients.

Alluvium consists of clay, silt, sand, gravel, or other unconsolidated material deposited by a stream or other body of running water as a sediment in the bed of a stream or on a floodplain or delta, or as a fan at the base of a mountain.

Anticline is an arched fold in which the rock layers dip away from the axis of the fold.

Aquifer is a body of rock that contains sufficient saturated, permeable material to yield substantial quantities of water to wells and springs.

Armored streambed is one having a coarser assemblage of particle sizes in the surface layer of bed material as compared to the subsurface composition. This condition results when the sediment-transport capacity of the stream over a wide range of flows is sufficient to move only the finer particle sizes of bed material.

Badlands refers to areas having intricately dissected topography resulting from fluvial erosion and characterized by high drainage density and steep, mostly barren sideslopes with narrow interfluvial ridges.

Bedrock is a general term for the consolidated (solid) rock that underlies soil or other unconsolidated surficial material.

Board foot is a unit of lumber measurement equal to 0.305 meter (1 foot) square by 25.4 millimeter (1 inch) thick.

Breccia refers to a coarse-grained clastic rock, composed of angular fragments bound by mineral cement or in a fine-grained matrix. The sharp edges and unworn corners of the fragments composing breccia differentiate it from conglomerate.

Caldera is a large, basin-shaped volcanic depression having a diameter many times greater than that of the included vent or vents.

Clastic rocks are composed principally of broken rock fragments that are derived from pre-existing rocks or minerals and have been transported from their place of origin. The most common clastic rocks are sandstone and shale.

Climax community refers to the final or stable biological community in a developmental series that is self-perpetuating and in equilibrium with the physical habitat.

Colluvium is heterogeneous, unconsolidated, incoherent soil or rock material.

Confined aquifer is bounded above and below by impermeable beds or by beds of distinctly lower permeability than that of the aquifer itself. In addition, the water level in a well open to a confined aquifer rises above the top of the aquifer.

Cubic meter per second (m^3/s) is the rate of discharge representing a volume of 1 cubic meter passing a given point during 1 second and is equivalent to about 264 gallons per second, or 35.31 cubic feet per second.

Discharge is the volume of water (or generally, the volume of liquid plus suspended material) that passes a given point within a given period. Discharge also is called flow.

Disseminated refers to a mineral deposit in which the desirable mineral occurs as scattered particles in the rock, but in sufficient quantity to make the deposit an ore.

Dissolved refers to a substance present in true chemical solution. In practice, however, the term includes all forms of substances that will pass through a 0.45-micrometer membrane filter, and thus may include some very small (colloidal) suspended particles.

Domestic water use is water for household purposes, such as drinking, preparing food, bathing, washing clothes and dishes, flushing toilets, and watering lawns and gardens. This water use is also called residential water use.

Drainage basin (drainage) is the total area drained by a stream and its tributaries. The area of a drainage basin is called drainage area and usually is determined planimetrically from topographic maps.

Ephemeral stream is a stream or reach of a stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.

Fault is a fracture in bedrock along which movement of the bedrock has occurred.

Flood plain is the lowland that borders a river, usually dry but subject to flooding when the stream overflows its banks.

Foreland structure is a geologic structural feature located along the edge of a stable continental platform and marginal to a belt of folded mountains.

Formation is a body of rock identified by unique physical characteristics and relative position.

Gaging station is a particular site on a stream, canal, lake, or reservoir where systematic observations of hydrologic data are obtained.

Greenstone belt refers to elongate areas within Precambrian shields that are characterized by altered or metamorphosed basic igneous rocks and sedimentary rocks forming one or more metamorphosed volcano-sedimentary piles.

Hogback refers to a sharp-crested ridge formed by the outcropping edges of steeply inclined resistant rocks, and produced by differential erosion.

Infiltration is the flow of water into soil at land surface, as contrasted with percolation, which is movement of water through soil layers or other surficial material.

Intermittent stream is a stream or reach of a stream that flows only certain times of the year when it receives water from springs or from some surface source such as melting snow.

Intrusive rocks are igneous rocks formed by emplacement of magma in pre-existing rocks.

Limestone is dense rock formed by chemical precipitation of calcium carbonate from solution in water.

Megagram is a unit of mass equivalent to 1,000 kilograms, one metric ton, or 1.102 short tons.

Metasedimentary rocks are sedimentary rocks that show evidence of having been subjected to metamorphism.

Milligrams per liter (mg/L) is a unit expressing the concentration of chemical constituents in solution as mass (milligrams) of solute per unit volume (liter) of water. Concentration of suspended sediment also is expressed in milligrams per liter and is based on the mass of sediment per liter of water-sediment mixture.

Orographic refers to precipitation patterns that result when moist air encounters a topographic barrier and is forced to rise over it; for example, the increase in precipitation with elevation on the windward slopes of a mountain range and the rain-shadow of decreased precipitation on the leeward side of the range.

Particle size (grain size) is the diameter, in millimeters, of any given sediment particle. (See particle-size classification.)

Particle-size classification used by the U.S. Geological Survey:

Classification	Particle-diameter range, in millimeters
Clay	0.00024-0.004
Silt	.004-.062
Sand	.062-2.00
Gravel	2.00-64.0

Peak discharge (peak flow, flood peak) is the maximum instantaneous discharge during a specified time interval. The series of annual peak discharges at a gaging station is used to determine the recurrence interval (frequency) and exceedance probability of floods.

Pediment refers to a broad, gently sloping, rock-floored erosional surface or plain of low relief, typically developed at the base of an abrupt, receding mountain front or plateau escarpment.

Perennial stream is a stream that flows continuously.

Permeability is a measure of the relative ease with which a porous or fractured medium can transmit a liquid under a potential gradient (the capacity of a rock to transmit a fluid such as water or petroleum).

pH is a measure of the acidity or alkalinity of water. It is defined as the negative logarithm of the hydrogen-ion concentration. This property is dimensionless and generally has a range from 0 to 14, with a pH of 7 representing neutral water. A pH of greater than 7 indicates the water is alkaline, whereas a pH value less than 7 indicates an acidic water.

Placer deposit is a surficial mineral deposit, usually of a heavy mineral, formed by mechanical concentration of mineral particles from weathered debris.

Porosity is the property of a rock or soil that refers to the voids that the material contains. It may be expressed quantitatively as the ratio of the volume of voids to total volume of the material.

Porphyry refers to an igneous rock that contains conspicuous phenocrysts (relatively large crystals) in a fine-grained groundmass.

Public-supply water use is water withdrawn by public and private water suppliers and delivered to users. Public suppliers provide water for a variety of uses, such as domestic, commercial, thermoelectric power, industrial, and public water use.

Recharge is the process by which water is absorbed and added to the saturated zone (aquifer), either directly into a body of rock or indirectly by way of an adjacent body of rock. Also, it is the quantity of water that is added to the saturated zone.

Riparian vegetation refers to plants growing in near-stream locations where more moisture is available to plants than in adjacent upland areas, and where the dominant species of adjacent upland vegetation are absent or compose a minor part of the community.

Sandstone is the consolidated equivalent of sand. (See particle-size classification.)

Saturated zone is the subsurface zone in which all openings are full of water and are under hydrostatic pressure equal to or greater than atmospheric pressure.

Sediment is unconsolidated solid material that originates mostly from disintegrated rocks and is transported by water or air. Also, it may include chemical and biochemical precipitates or decomposed organic material, such as humus.

Shale is the consolidated equivalent of clay. (See particle-size classification.)

Shear zone is a tabular zone of rock that has been crushed and brecciated by many parallel fractures due to shear strain. Shear zones often are mineralized by ore-forming solutions.

Siltstone is the consolidated equivalent of silt. (See particle-size classification.)

Silviculture (forestry) is the care and cultivation of forest trees.

Skarn refers to lime-bearing silicates derived from limestone and dolomite with the introduction of large amounts of Si, Al, Fe and Mg.

Stock is an igneous intrusion having less than 100 km^2 of surface exposure; resembles a batholith except in size.

Stratification refers to a statistical design for study or sampling in which a population is first divided into groups, or strata, having greater homogeneity than the whole population, according to relevant characteristics; then information is gathered about each group, often by selecting a sample from each.

Stratiform refers to geologic structure having the form of a layer, bed, or stratum; consisting of roughly parallel bands or sheets.

Streamflow is the discharge in a natural channel. Although the term "discharge" can be applied to a flow of a canal, the word "streamflow" is used only to describe the discharge in a stream. The term "streamflow" is more general than "runoff," since streamflow may be applied to discharge whether or not it is affected by diversion or regulation.

Superimposed refers to a stream or drainage system that has cut down from above by erosion, through the formations on which it developed, onto rocks of different structure lying beneath.

Surface water is an open body of water such as a stream or lake.

Terrace is a steplike landform above a stream and its floodplain, representing a former, abandoned floodplain of a stream.

Unconsolidated refers to sediment grains that are loose, separate, or unattached to one another.

Unsaturated zone is the zone between the land surface and the water table. It includes the capillary fringe. Generally, water in this zone is under less than atmospheric pressure, and some of the voids may contain air or other gases at atmospheric pressure.

Volcaniclastic refers to a clastic rock containing volcanic material.

Water table refers to the upper surface of the saturated zone where the water pressure is equal to atmospheric pressure.

Water year refers to the 12-month period from October 1 to September 30, and is designated by the calendar year in which it ends. Thus, the water year ending on September 30, 1995, is called water year 1995.

Yield is the constant or final pumping rate from a well in liters per minute at which a well-acceptance test is conducted.

Table 16. *Lithologic, water-yielding characteristics, and water quality of major geologic units in the Yellowstone River Basin that lie within the Wind River, Bighorn, and Powder River Basins*

(Table modified from Plafcan and others, 1995; Plafcan and Ogle, 1994; Plafcan and others, 1993; and Lowry and others, 1993)

[m, meters; m/d, m per day; mg/L, milligrams per liter; µg/L, micrograms per liter; L/min, liters per minute; yields: small, less than 190 L/min; moderate, 190-1,100 L/min; large, more than 1,100 L/min; --, no data]

System	Series	Geologic unit	Lithology	Water-yielding characteristics	Water quality	Basins where geologic units are present
Quaternary	Sequence in table does not indicate position relative to other Quaternary entries	Alluvium and colluvium	“Unconsolidated clay, silt, sand, and gravel; includes terrace, flood-plain, and pediment deposits along major streams.”[1, 2] “Silt, sand, and gravel, unconsolidated; underlies flood plains and bordering terraces.”[2] “Clay, silt, sand, and gravel in flood plains, fans, terraces, and slopes.”[3]	Yield small to large supplies of water; large yields could be developed in some areas.[1, 2]	“The chemical quality of water in alluvial deposits differs from place to place, depending on the source and amount of recharge, and type of bedrock underlying the alluvium. Water in the flood-plain deposits of perennial streams is generally good in the upper reaches of the stream, but the quality deteriorates downstream.” [1] Water in alluvium near Bighorn Mountains is better quality than water in alluvium in central part of Powder River Basin.[2]	Wind River, Bighorn, Powder River
Quaternary	Sequence in table does not indicate position relative to other Quaternary entries	Dune sand and loess	“Unconsolidated fine to very fine sand; present in eastern part of the Wind River Basin.”[1]	“Yields small supplies of water of suitable quality for stock or domestic use; it is an important source of water in areas underlain by the Cody Shale.”[1] Unknown in Bighorn and Powder River Basins.	Water is of good quality in Wind River Basin.[1] Unknown in Bighorn and Powder River Basins.	Wind River, Bighorn, Powder River
Tertiary	Oligocene	White River Formation	“White to pale-pink blocky tuffaceous claystone and lenticular arkosic conglomerate.”[3] Present in the southeastern part of the Wind River Basin.[1]	“Highly permeable and productive water-bearing unit. Good intergranular permeability and porosity. Well yields generally range between 4 to 1,100 L/min, with maximum reported production 3,200 L/min. Saturated thickness ranges between 60 to 110 m.”[4] Present as isolated remnants in southwest Campbell County (Pumpkin Buttes), otherwise absent from Powder River Basin within the study unit.[3]	Dissolved-solids concentrations of historical water samples taken in the Wind River Basin ranged from 207 to 397 mg/L. The water was a calcium carbonate type.	Wind River, Powder River

Table 16. *Lithologic, water-yielding characteristics, and water quality of major geologic units in the Yellowstone NAWQA Study Unit Area that lie within the Wind River, Bighorn, and Powder River Basins--Continued*

System	Series	Geologic unit	Lithology	Water-yielding characteristics	Water quality	Basins where geologic units are present
Tertiary	Eocene	Tepee Trail Formation[5]	"Green and olive-drab hard and generally well bedded andesitic conglomerate, sandstone, and claystone."[3]	"Yields minor amounts (less than 38 L/min) of water to springs and shallow wells along outcrop. Confining layer."[4]	Limited water quality data (three samples) showed that dissolved-solids concentrations ranged from 197 to 244 mg/L.	Wind River
Tertiary	Eocene	Aycross Formation[5]	"Brightly variegated bentonitic claystone and tuffaceous sandstone, grading laterally into greenish-gray sandstone and claystone."[3]	"Would probably yield at least small, and possibly large, supplies from sandstone and conglomerate beds"[1] "Confining layer."[4] Localized water yield primarily a function of sandstone content. Sandstone presence highly variable both vertically and laterally.	Unknown.	Wind River, Bighorn
Tertiary	Eocene	Wagon Bed Formation	"Green and gray tuffaceous claystone, sandstone, and conglomerate; some uranium-phosphate marlstone and variegated bentonitic claystone. Locally contains oil shale between Wind River and Bighorn Basins."[3]	"Yields water locally to springs and shallow wells. Yields less than 38 L/min. Saturated zones include sandstone and conglomerate lenses... Not considered an aquifer."[3]	Dissolved-solids concentrations of historical water samples taken in the Wind River Basin ranged from 207 to 572 mg/L. The water was a calcium-sodium carbonate type.	Wind River
Tertiary	Eocene	Wasatch Formation	Locally derived conglomerate around Wind River Basin margins. Lower part is Paleocene.[3] Drab sandstone and drab to variegated claystone; numerous coal beds in lower part of Powder River Basin.[3]	Yields water from lenticular sandstone, and to a lesser extent from jointed coal and clinker beds. Yields can be expected to range from 10 to 190 L/min in north part of Powder River Basin becoming generally greater southward with 1,900 L/min or more possible in south part of basin.[2] Unknown in Wind River Basin.	Dissolved-solids concentrations of historical water samples taken in the Powder River Basin ranged from less than 200 to more than 8,000 mg/L, but commonly ranged between 500 and 1,500 mg/L. Sodium sulfate and sodium bicarbonate were the dominant water types.[2] Unknown in Wind River Basin.	Wind River Powder River

Table 16. *Lithologic, water-yielding characteristics, and water quality of major geologic units in the Yellowstone NAWQA Study Unit Area that lie within the Wind River, Bighorn, and Powder River Basins--Continued*

System	Series	Geologic unit	Lithology	Water-yielding characteristics	Water quality	Basins where geologic units are present
Tertiary	Eocene	Wind River Formation	“Variegated claystone and sandstone; lenticular conglomerate.”[3]	“Large supplies have been developed in the Riverton and Gas Hills areas and could be developed elsewhere, especially along the margin of the basin. Yields small supplies to many widely distributed stock and domestic wells”[1, 6] Major aquifer in Wind River Basin. “Yields water to wells and springs throughout basin.”[4] Yields range between 4 to 11,000 L/min. Locally contains artesian zones with sufficient head to produce 760 L/min. “Principal source of domestic and stock water on Wind River Reservation. Principal source of industrial water in southern part of basin”[4]	Dissolved-solids concentrations of historical water samples taken in the Wind River Basin ranged from 248 to 5,110 mg/L. The water was a sodium-calcium sulfate type. One water sample analyzed for specific trace elements contained a selenium concentration of 58 µg/L, which is above the Maximum Contaminant Level of 50 µg/L set by the U.S. Environmental Protection Agency.	Wind River
Tertiary	Eocene	Indian Meadows Formation	“Series of variegated claystone, argillaceous sandstone, massive limestone, and poorly sorted conglomerate.”[4]	“Confining layer.”[4]	Unknown.	Wind River
Tertiary	Eocene	Willwood Formation	Variegated, interbedded claystone and channel sandstone. Averages about 25 percent sandstone.	Might yield enough water from sandstones for domestic or stock use.	Dissolved-solids concentrations of historical water samples taken in the Bighorn Basin ranged from 232 to 9,000 mg/L.	Bighorn

Table 16. *Lithologic, water-yielding characteristics, and water quality of major geologic units in the Yellowstone NAWQA Study Unit Area that lie within the Wind River, Bighorn, and Powder River Basins--Continued*

System	Series	Geologic unit	Lithology	Water-yielding characteristics	Water quality	Basins where geologic units are present
Tertiary	Paleocene	Fort Union Formation	Conglomerate, sandstone, shale, and carbonaceous shale in lower part of formation grading into very fine grained clastics in upper part, present at depth throughout most of the Wind River Basin.[1] Northwest and central Wyoming—brown to gray sandstone, gray to black shale, and thin coal beds.[3] “Conglomerate, sandstone, shale, siltstone, and carbonaceous shale in basal part of unit; grades upward to very fine-grained clastics.”[4]	Sandstones yield small supplies of water that is generally unsuitable for domestic use and may be marginal for stock in Wind River Basin.[1] “Conglomerate and sandstone zones yield water to wells. Highly productive and permeable where fractured. Water is semi-confined to confined with sufficient head to produce 38 L/min... Basal part of unit is considered a regional confining unit. Upper part of unit contains complex series of permeable and confining layers.”[4] Yields water from fine-grained sandstone, jointed coal, and clinker beds. Maximum yields are about 570 L/min in Powder River Basin.[2] Might yield enough water from sandstones for domestic or stock use in Bighorn Basin.	Historic water quality data from two samples taken in the Wind River Basin had dissolved-solids concentrations of 994 and 5,110 mg/L. Dissolved-solids concentrations of historical water samples taken in the Bighorn Basin ranged from 623 to 4,890 mg/L. Samples taken in the Powder River Basin ranged from about 200 to more than 3,000 mg/L, but commonly range between 500 and 1,500 mg/L. Water was mostly sodium bicarbonate, and to a lesser extent sodium sulfate.[2]	Wind River, Bighorn, Powder River
Cretaceous	Upper Cretaceous	Lance Formation	“North Wyoming—thick-bedded buff sandstone and drab to green shale; thin conglomerate lenses.... Northeast Wyoming—brown and gray sandstone and shale; thin coal and carbonaceous shale beds.”[3]	“No known wells produce water solely from unit. Wells completed in Fort Union and Lance Formations. Unit is highly productive and permeable in Big Horn basin (yields range between 4 to 380 L/min)... Large development potential in Wind River Basin.”[4] Generally yields less than 76 L/min, but yields of several hundred liters per minute may be possible from the complete section of the formation in Powder River Basin.[2]	Dissolved-solids concentrations of historical water samples taken in the Bighorn Basin ranged from 591 to 1,860 mg/L. Dissolved-solids concentrations of historical water samples taken in the Powder River Basin ranged from about 200 to more than 2,000 mg/L, but commonly ranged between 500 and 1,500 mg/L. No dominant water type was prevalent.[2] Unknown in Wind River Basin.	Wind River, Bighorn, Powder River

Table 16. *Lithologic, water-yielding characteristics, and water quality of major geologic units in the Yellowstone NAWQA Study Unit Area that lie within the Wind River, Bighorn, and Powder River Basins--Continued*

System	Series	Geologic unit	Lithology	Water-yielding characteristics	Water quality	Basins where geologic units are present
Cretaceous	Upper Cretaceous	Fox Hills Sandstone	"Light-colored sandstone and gray sandy shale containing marine fossils."[3]	Maximum yields in west part of Powder River Basin will probably be less than 380 L/min.[2]	Dissolved-solids concentrations of historical water samples taken in the eastern Powder River Basin were generally less than 1,000 mg/L, but generally ranged between 1,000 and 2,000 mg/L in west part. No dominant water type was prevalent.[2]	Powder River
Cretaceous	Upper Cretaceous	Meeteetse Formation	"Chalky-white to gray sandstone, yellow, green, and dark-gray bentonitic claystone, white tuff, and thin coal beds."[3]	Sandstones yield small supplies of water that is generally unsuitable for domestic use and may be marginal for stock in Wind River Basin." "Regional confining layer."[4] Sandstone might yield enough water for domestic or stock use in Bighorn Basin.	Dissolved-solids concentrations of historical water samples taken in the Bighorn Basin ranged from 936 to 2,920 mg/L. Unknown in Wind River Basin.	Wind River, Bighorn
Cretaceous	Upper Cretaceous	Lewis Shale (Bear Paw Shale)	"Gray marine shale containing many gray and brown lenticular concretion-rich sandstone beds."[3]	Sandstones yield small supplies of water that is generally unsuitable for domestic use and may be marginal for stock in Wind River Basin.[1] Sandy zones may yield as much as 38 L/min, but most of the formation does not yield water in Powder River Basin.[2]	Unknown.	Wind River, Bighorn, Powder River
Cretaceous	Upper Cretaceous	Mesaverde Formation	"Light-colored massive to thin-bedded sandstone, gray sandy shale, and coal beds."[3]	Permeable and productive water-bearing unit. Regional aquifer. Well yield data not available; however, artesian flows reported in numerous petroleum tests in central Wind River Basin.[4] Yields of as much as 190 L/min are possible from sandstone beds, and as much as 760 L/min where fracturing has increased the permeability, generally near geologic structures.[2]	Dissolved-solids concentrations of historical water samples taken in the Wind River and Bighorn Basins ranged from 688 to 5,510 mg/L. The water type was variable. Dissolved-solids can be expected to range from about 300 to more than 2,000 mg/L in the Powder River Basin. Most water will be sodium sulfate type.[2]	Wind River, Bighorn, Powder River

Table 16. *Lithologic, water-yielding characteristics, and water quality of major geologic units in the Yellowstone NAWQA Study Unit Area that lie within the Wind River, Bighorn, and Powder River Basins--Continued*

System	Series	Geologic unit	Lithology	Water-yielding characteristics	Water quality	Basins where geologic units are present
Cretaceous	Upper Cretaceous	Cody Shale	"Dull-gray shale, gray siltstone, and fine-grained gray sandstone."[3]	Yields only meager supplies of poor quality water in Wind River Basin.[1] "Regional confining layer."[4] Yields of as much as 76 L/min possible from sandstone beds, but other rocks in formation would yield little or not water in Powder River Basin.[2] Thin sandstone might yield enough water locally for domestic or stock use in Bighorn Basin.	Dissolved-solids concentrations of historical water samples taken in all three basins ranged from around 700 to over 8,000 mg/L. The water was a sodium sulfate type in the Bighorn and Powder River Basins.	Wind River, Bighorn, Powder River
Cretaceous	Upper Cretaceous	Frontier Formation	"Gray sandstone and sandy shale."[3]	Yields small quantities of generally poor quality water although some supplies are usable for domestic purposes in Wind River Basin."[1] Upper two-thirds of unit is regional aquifer in Wind River Basin; lower one-third of unit is confining layer. Water is under confined conditions with sufficient head to produce flows of 38 to 95 L/min at selected petroleum tests. Yields 19 to 570 L/min to shallow stock and domestic wells"[4] Yields of as much as 190 L/min are available from sandstone beds in Powder River Basin.[2] Artesian conditions exist in the area along Kirby Creek in the Bighorn Basin.	Dissolved-solids concentrations of historical water samples taken in the Wind River and Bighorn Basins ranged from 280 to 9,960 mg/L. The water type was variable. Dissolved-solids can be expected to range from about 300 to more than 3,000 mg/L in the Powder River Basin. Most water is sodium bicarbonate or sodium sulfate type.[2]	Wind River, Bighorn, Powder River
Cretaceous	Upper Cretaceous	Mowry Shale	"Silvery-gray hard siliceous shale containing abundant fish scales and bentonite beds."[3]	Regional confining layer in Wind River Basin.[4] Some of these rocks may yield as much as 38 L/min, but most of the formation does not yield water in Powder River Basin..[2] Might yield very limited quantities of water to wells where fractured in Bighorn Basin.	Historic water quality data from one sample taken in the Wind River Basin had a dissolved-solids concentration of 648 mg/L. Dissolved-solids concentrations of historical water samples taken in the Bighorn Basin ranged from 362 to 1,150 mg/L. Unknown in Powder River Basin.	Wind River, Bighorn, Powder River

Table 16. *Lithologic, water-yielding characteristics, and water quality of major geologic units in the Yellowstone NAWQA Study Unit Area that lie within the Wind River, Bighorn, and Powder River Basins--Continued*

System	Series	Geologic unit	Lithology	Water-yielding characteristics	Water quality	Basins where geologic units are present
Cretaceous	Lower Cretaceous	Thermopolis Shale	“Black soft fissile shale; Muddy Sandstone Member at top.”[3]	Regional confining layer in Wind River Basin.[4] Ground-water possibilities not known in Powder River Basin, but probably poor.[2] Shales are relatively impermeable. Wells developed in Muddy Sandstone Member may yield enough water for domestic or stock use in Bighorn Basin.	Historic water quality data from two samples taken in the Wind River Basin had dissolved-solids concentrations of 223 and 525 mg/L. Dissolved-solids concentrations of historical water samples taken in the Bighorn Basin ranged from 599 to 1,100 mg/L. Unknown in Powder River Basin.	Wind River, Bighorn, Powder River
Cretaceous	Lower Cretaceous	Cloverly Formation	North Wyoming—“rusty sandstone at top, underlain by brightly variegated bentonitic claystone; chert-pebble conglomerate locally at base. Northeast Wyoming—rusty to light-gray sandstone containing lenticular chert-pebble conglomerate interbedded with variegated bentonitic claystone.”[3]	“Yield small to moderate supplies of water suitable for domestic use near outcrops”[1] Permeable and productive upper and basal sandstones in Wind River Basin. Water is under artesian conditions with sufficient head to produce flows of 4 to 95 L/min at selected petroleum tests. Yields water to stock wells along outcrops.[4, 6] Most yields range from 19 to 76 L/min in the Powder River Basin, but yields of 380 L/min or more are possible from complete section of rocks, and as much as several hundred liters per minute from zones of secondary permeability.[2] Sandstones might yield enough water for stock or domestic use in Bighorn Basin.	Dissolved-solids concentrations of historical water samples taken in all three basins generally ranged from 300 to 3,000 mg/L. Sodium sulfate was the dominant water type in the Powder River Basin.[2]	Wind River Bighorn Powder River
Jurassic		Morrison Formation	“North Wyoming—dully variegated claystone, nodular limestone, and gray silty sandstone. Northeast Wyoming—dully variegated siliceous claystone, nodular white limestone, and gray silty sandstone”[3]	Sandstones may yield enough water for domestic or stock use.	Dissolved-solids concentrations of historical water samples taken in the Wind River Basin ranged from 798 to 1,710 mg/L. Historic water quality data from one sample taken in the Bighorn Basin had a dissolved-solids concentration of 673 mg/L. Unknown in Powder River Basin.	Wind River Bighorn Powder River

Table 16. *Lithologic, water-yielding characteristics, and water quality of major geologic units in the Yellowstone NAWQA Study Unit Area that lie within the Wind River, Bighorn, and Powder River Basins--Continued*

System	Series	Geologic unit	Lithology	Water-yielding characteristics	Water quality	Basins where geologic units are present
Jurassic		Sundance Formation	"Greenish-gray glauconitic sandstone and shale, underlain by red and gray nonglauconitic sandstone and shale."[3]	"Yield small to moderate supplies of water suitable for domestic use near outcrops"[1] Regional aquifer in Wind River Basin. Large intergranular permeability in sandstone and chert lenses. Yields water to shallow stock and domestic wells along outcrops (4 to 95 L/min).[4] Sandstone beds in Powder River Basin will probably yield no more than 76 L/min.[2] Sandstones might yield enough water for stock or domestic use in Bighorn Basin.	Dissolved-solids concentrations of historical water samples taken in the Bighorn Basin ranged from 331 to 1,750 mg/L. Dissolved-solids can be expected to range from about 500 to more than 2,000 mg/L in the Powder River Basin. No water type is dominant.[2] Unknown in Wind River Basin.	Wind River Bighorn Powder River
Jurassic		Gypsum Spring Formation	"Interbedded red shale, dolomite, and gypsum. In north Wyoming wedges out south in T. 39 N."[3]	No water wells known to tap this formation in the Wind River Basin, but it would probably yield only poor quality water.[1] "Regional confining layer."[4] Solution zones in gypsum beds yield small amounts of water in Bighorn Basin.[7] Yields a few liters per minute locally for stock purposes from solution cavities in or near outcrop areas in the Powder River Basin.[2]	Historic water quality data from one sample taken in the Wind River Basin had a dissolved-solids concentration of 1,360 mg/L. Dissolved-solids concentrations of historical water samples taken in the Bighorn Basin ranged from 287 to 2,650 mg/L. Dissolved-solids are generally greater than 1,000 mg/L in the Powder River Basin, the dominant water type is calcium sulfate.[2]	Wind River Bighorn Powder River
Jurassic(?)-Triassic(?)		Nugget Sandstone	"Gray to dull-red crossbedded quartz sandstone."[3]	"Water-bearing potential not known in Wind River Basin, but probably would yield small supplies, and larger supplies might be developed in some areas"[1] Water-yielding characteristics unknown in Bighorn Basin.	Historic water quality data from one sample taken in the Wind River Basin had a dissolved-solids concentration of 1,470 mg/L. Unknown in Bighorn Basin.	Wind River Bighorn

Table 16. *Lithologic, water-yielding characteristics, and water quality of major geologic units in the Yellowstone NAWQA Study Unit Area that lie within the Wind River, Bighorn, and Powder River Basins--Continued*

System	Series	Geologic unit	Lithology	Water-yielding characteristics	Water quality	Basins where geologic units are present
Triassic		Chugwater Formation	"Red siltstone and shale. Alcova Limestone Member in upper middle part in north Wyoming. Thin gypsum partings near base in north and northeast Wyoming."[3]	Yields small supplies of good quality water in and near outcrops in Wind river Basin.[1] Will probably yield as much as 76 L/min in Powder River Basin.[2] May yield sufficient quantities of water to wells for domestic and stock use in the Bighorn Basin.	Dissolved-solids concentrations of historical water samples taken in the Wind River and Bighorn Basins ranged from 251 to 2,940 mg/L. The water type was calcium sulfate. Dissolved-solids generally range from about 500 to more than 1,000 mg/L in the Powder River Basin, the dominant water type is calcium sulfate.[2]	Wind River Bighorn Powder River
Triassic		Dinwoody Formation	"Olive-drab hard dolomitic thin-bedded siltstone."[3]	Yields small supplies of good quality water in and near outcrops in Wind River Basin.[1] Water-yielding characteristics unknown in Bighorn Basin.	Yields small supplies of good quality water in and near outcrops in Wind River Basin.[1] Unknown in Bighorn Basin.	Wind River Bighorn
Triassic and Permian		Goose Egg Formation	"Red sandstone and siltstone, white gypsum, halite, and purple to white dolomite and limestone."[3]	Probably would yield only small supplies of mineralized water in Wind River Basin.[1] Yields little or no water in Powder River Basin.[2] Might yield small quantities of water to wells as a result of dissolution of gypsum in Bighorn Basin.	Dissolved-solids concentrations of historical water samples taken in the Bighorn Basin ranged from 205 to 2,230 mg/L. Unknown in Wind River and Powder River Basins.	Wind River Bighorn Powder River
Permian		Phosphoria Formation and related rocks	"Brown sandstone and dolomite, cherty phosphatic and glauconitic dolomite, phosphatic sandstone and dolomite, and greenish-gray to black shale."[3]	"Complex series of permeable sandstones and impermeable limestone, dolomite and siltstone. Highly productive where fractured. Well yields range up to 3,800 L/min"[4] Yields as large as 3,800 L/min observed in Bighorn Basin.	Dissolved-solids concentrations of historical water samples taken in the Wind River and Bighorn Basins ranged from 215 to 3,690 mg/L. The water type was variable.	Wind River Bighorn

Table 16. *Lithologic, water-yielding characteristics, and water quality of major geologic units in the Yellowstone NAWQA Study Unit Area that lie within the Wind River, Bighorn, and Powder River Basins--Continued*

System	Series	Geologic unit	Lithology	Water-yielding characteristics	Water quality	Basins where geologic units are present
Permian and Pennsylvanian		Tensleep Sandstone	"North Wyoming—white to gray sandstone containing thin limestone and dolomite beds. Permian fossils have been found in the topmost beds of the Tensleep at some localities in... Owl Creek Mountains."[3]	Uppermost unit of the Tensleep aquifer system. Good intergranular permeability, excellent permeabilities where fractured. Saturated throughout Wind River Basin. Water is under confined conditions with sufficient head to produce flows of 4 to several hundred L/min from selected wells.[4] Yields ranging from 76 L/min to as much as several hundred L/min are possible from these rocks, and where fracturing has increased the permeability, yields greater than 3,800 L/min may be possible in the Powder River Basin.[2, 8] Flowing wells along the western flank of the Bighorn Mountains yield large dependable supplies of water.	Dissolved-solids concentrations of historical water samples taken in the Wind River and Bighorn Basins ranged from 171 to 3,480 mg/L. The water type was calcium-magnesium carbonate in the Wind River Basin. "Dissolved solids commonly range from 200 to 500 mg/L and are generally less than 1,000 mg/L, but locally may be more than 2,000 mg/L."[2]	Wind River, Bighorn, Powder River
Pennsylvanian and Mississippian		Amsden Formation	"North Wyoming—red and green shale and dolomite; at base is brown sandstone."[3]	Part of Tensleep aquifer system. Sandstone member is permeable along joints and partings between bedding planes. Excellent permeabilities where fractured. Water is confined. Well yields range between 4 to several hundred L/min in Wind River Basin.[4]	Unknown.	Wind River, Bighorn, Powder River
Mississippian		Madison Limestone or Madison Group	Massive to thin bedded limestone, containing some thin beds of chert and red shales near the top.[1] "Massive crystalline limestone and dolomite with siltstone and shale zones, cherty in places."[7] "Dolomite and limestone, massive to thin bedded, cavernous in upper part"[2]	Part of Tensleep aquifer system. Poor permeabilities except where fractured. Some saturated caverns. Water-bearing throughout Wind River Basin. Water is confined. Well yields range between 4 to several hundred L/min.[4] Yields of more than 3,800 L/min are available where cavernous and fractured zones are present in Powder River Basin.[2] Unit in hydraulic connection with underlying Bighorn Dolomite forming the Madison-Bighorn aquifer in Bighorn Basin.	Dissolved-solids concentrations of historical water samples taken in all three basins ranged from 169 to 3,390 mg/L. Water type in Powder River Basin was sodium sulfate. One sample in the Wind River Basin was a calcium-magnesium carbonate water type. One sample in the Bighorn Basin was a calcium sulfate water type.	Wind River, Bighorn, Powder River

Table 16. *Lithologic, water-yielding characteristics, and water quality of major geologic units in the Yellowstone NAWQA Study Unit Area that lie within the Wind River, Bighorn, and Powder River Basins--Continued*

System	Series	Geologic unit	Lithology	Water-yielding characteristics	Water quality	Basins where geologic units are present
Devonian		Darby Formation	"Yellow and greenish-gray shale and dolomitic siltstone underlain by fetid brown dolomite and limestone."[3]	"Part of Tensleep aquifer system. Generally considered a confining layer, but permeable along joints and fractures. Numerous joint controlled springs along Wind River Mountains."[4] May hydrologically separate the overlying Madison Limestone from the underlying Bighorn Dolomite.	Unknown.	Wind River, Bighorn
Ordovician		Bighorn Dolomite	"Gray massive cliff-forming siliceous dolomite and locally dolomitic limestone."[3]	"Basal part of Tensleep aquifer system. Basal sandstones are permeable; also permeable along joints and fractures. Yields water to numerous springs along Wind River Mountains."[4] Yields ranging from 76 L/min to several hundred liters per minute should be available from solution cavities and fractures in Powder River Basin.[2] In combination with the Darby Formation and the Madison Limestone, forms the Madison-Bighorn aquifer in the Bighorn Basin, which produces large and dependable supplies of potable water.[7]	Historic water quality data from two samples taken in the Wind River Basin had a dissolved-solids concentration of 102 and 178 mg/L. Dissolved-solids concentrations of historical water samples taken in the Bighorn Basin ranged from 196 to 3,440 mg/L. Unknown in Powder River Basin.	Wind River, Bighorn, Powder River
Cambrian		Gallatin Limestone	"Blue-gray and yellow mottled hard dense limestone."[3]	"Confining layer. Permeable along joints and fractures. Yields small quantities (less than 19 L/min) to springs along the Wind River Mountains."[4] Probably yields less than 38 L/min in Powder River Basin. [2, 9] In combination with underlying Gros Ventre Formation, forms a confining layer for the Flathead Sandstone in Bighorn Basin.	Historic water quality data from one sample taken in the Bighorn Basin had a dissolved-solids concentration of 296 mg/L. The water type was magnesium bicarbonate. Unknown in Wind River and Powder River Basins.	Wind River, Bighorn, Powder River

Table 16. *Lithologic, water-yielding characteristics, and water quality of major geologic units in the Yellowstone NAWQA Study Unit Area that lie within the Wind River, Bighorn, and Powder River Basins--Continued*

System	Series	Geologic unit	Lithology	Water-yielding characteristics	Water quality	Basins where geologic units are present
Cambrian		Gros Ventre Formation	“Limestone, shale, and calcareous shale, flat-pebble conglomerate at base.”[4] “Green-gray thin-bedded limestone and limestone-pebble conglomerate.”	“Ground-water possibilities not known, but rocks are potential sources of large supplies where fractured or cavernous.”[1] “Confining layer.”[4] Probably would yield less than 38 L/min in Powder River Basin.[2, 10] Thin sandstone beds indicate potential for small yields in Bighorn Basin.	Unknown.	Wind River, Bighorn, Powder River
Cambrian		Flathead Sandstone	“Dull-red quartzitic sandstone.”[3]	Major aquifer in Wind River Basin. Permeable along partings between bedding planes, faults, fractures and joints. Small interstitial permeabilities. Water is semi-confined to confined. Yields 4 to 19 L/min to shallow stock and domestic wells. Excellent ground-water resource potential; however, relatively undeveloped because of availability of shallower ground-water sources.[4] Yields of 76 L/min are probably available in the Powder River Basin. [2, 11] Yields over 7,600 L/min reported in Bighorn Basin.[7]	Dissolved-solids concentrations of historical water samples taken in the Wind River and Bighorn Basins ranged from 37 to 443 mg/L. Three samples from Hot Springs County in the Bighorn Basin were a calcium bicarbonate water type. Unknown in Powder River Basin.	Wind River, Bighorn, Powder River

[1]Whitcomb and Lowry, 1968.
[2]Hodson and others, 1973.
[3]Love and Christiansen, 1985.
[4]Richter, Jr., 1981.
[5]Part of the Absaroka Volcanic Supergroup.
[6]Includes Morrison Formation.
[7]Libra and others, 1981.
[8]Includes Amsden, Hartville, and Minnelusa Formations.
[9]Includes Whitewood Dolomite, Winnipeg, and Gros Ventre Formations.
[10]Includes Whitewood Dolomite, Winnipeg, and Gallatin Formations.
[11]Includes Deadwood Formation.

Table 17. *Shallow Hydrogeologic Units in the Powder River Basin, Montana and Wyoming*

(Table modified from Lewis and Hotchkiss, 1981)

[m, meters; L/min, liters per minute]

Hydrogeologic Unit	Range of Thickness (m)	General Description	Water-Yielding Characteristics
Wasatch-Tongue River aquifer	0-1,190	Includes interfingering lenses of gravel, sand, silt, and clay of alluvium or terrace deposits (not shown on map) near the major streams and their tributaries; tuffaceous bentonitic claystone and siltstone which grade downward into lenticular fine-grained sandstone of the White River Formation; brownish-gray fine- to coarse-grained lenticular sandstone, interbedded with shale and coal, weathering to a buff color and the clinker deposits near coal outcrops of the Wasatch Formation; light-yellow to light-gray fine- to medium-grained thick-bedded to locally massive cross-bedded and lenticular, calcareous sandstone and siltstone, weathering to a buff color, thick and laterally persistent coal beds, and clinker deposits near coal outcrops of the Tongue River Member of the Fort Union Formation; and may contain light-gray fine- to medium-grained sandstones and siltstones of the upper part of the Lebo Shale Member of the Fort Union Formation	Yields range from 19 to 380 L/min for alluvium and from 10 to 610 L/min for sandstone, coal, or clinker deposits; most wells are shallow in the upper part of the unit. In the southern part of the basin yields as much as 1,900 L/min may be possible from sandstone or clinker deposits with proper well construction; well yields of 38-190 L/min have been measured. Wells completed in the lower part of the aquifer may flow as much as 38 L/min. Unit is an aquifer everywhere clinker deposits exist in the saturated zone
Lebo confining layer	0-920	Dark shale predominates with interbedded light-gray and brown to black carbonaceous shale, siltstone, and locally thin coal beds of the Lebo Shale Member of the Fort Union Formation. Altered and devitrified volcanic ash and brown ferruginous concretions are present in shale	Functions as a retarding layer within the study area; may yield as much as 38 L/min to wells locally where sufficient saturated thickness of lenticular channel deposits is penetrated
Tullock aquifer	0-600	Includes light-gray fine- to medium grained channel sandstone near the base of the Lebo Shale Member where present plus light-gray sandy or silty shale, locally resistant sandstone which grades downward into interbedded medium-gray to light-gray shale, light-gray fine-grained sandstone and siltstone, and thin coalbeds of the Tullock Member of the Fort Union Formation	Yields from fine-grained sandstones and jointed coal beds may be as much as 150 L/min but yields of 57 L/min are more common. Where aquifer is confined, wells generally flow less than 38 L/min

Table 17. *Shallow Hydrogeologic Units in the Powder River Basin, Montana and Wyoming--Continued*

Hydrogeologic Unit	Range of Thickness (m)	General Description	Water-Yielding Characteristics
Upper Hell Creek confining layer	0-610	Interbedded gray to brown siltstone and shale, locally lenticular fine- to medium-grained sandstone, and interbedded claystone, thin coal beds, silty sandstone, and bentonitic shale of the upper part of the Hell Creek (or Lance) Formation	Limited water supply in study area; functions as a major retarding unit. Locally, flowing wells tapping sandy deposits yield as much as 15 L/min
Fox Hills-Lower Hell Creek aquifer	0-780	Interbedded carbonaceous shale, sandy shale, siltstone, and claystone with local deposits of gray to brown silty to clayey often crossbedded sandstone of the lower part of the Hell Creek (or Lance) Formation plus the marine gray to light-tan fine- to medium-grained sandstone of the Fox Hills Sandstone; locally contains thin beds of sandy shale	Yields as much as 760 L/min to properly constructed wells, with yields generally less than 380 L/min. Reliable source of water for artesian wells; wells flow as much as 76 L/min along major river valleys

Table 18. *Hydrogeology of southeastern Montana*

(Table modified from Stoner and Lewis, 1980)

[m, meters; mm, millimeters; L/min, liters per minute]

Hydrogeologic Unit	Range of Thickness (m)	General Description	Water-Yielding Characteristics
Alluvial aquifer	2-40	Includes lake-basin deposits, unconsolidated flood-plain deposits, and adjacent terrace deposits less than 15 m above current stream level—Largely unconsolidated sand, silt, and clay with local lenses of gravel. Coarse well-rounded gravel interbedded with finer material is common in basal alluvial deposits along the Yellowstone and Missouri Rivers, probably derived from reworked terrace gravels.	Coarse gravels along the Missouri River are reported to yield as much as 1,900 L/min to large-diameter wells; along smaller streams and adjacent low-lying terraces, yields of 380 L/min might be possible. Yields average about 57 L/min to stock and domestic wells.
Terrace gravel aquifer	2-30	Comprises terraces of Crane Creek, Cartwright, Flaxville, and Rimroad Gravels as described by Howard (1960)—Mostly gravel and sand with some silt and clay. Well-rounded 25- to 300-mm-diameter cobbles and boulders and sand-size particles of quartzite, chert, and igneous rocks are common. Deposits are largely distributed along upland areas and benches of the Yellowstone river. Many of the higher deposits are covered by loess.	Terraces are mostly isolated, topographically high units having limited saturation. Yields may be as much as 76 L/min to domestic and stock wells centrally located within larger deposits and along major streams at lower altitudes.
Wasatch-Tongue River aquifer	1-880	Consists mostly of Tongue River Member of Fort Union Formation but locally includes overlying basal rocks of Wasatch Formation—Light-gray to brownish-gray fine-to medium-grained thick bedded to massive and locally crossbedded lenticular calcareous sandstone and siltstone. Commonly weathers light yellow to buff. Contains light-buff to dark-gray shaly siltstone and shale, brown to black carbonaceous shale, and coal beds as thick as 25 m.	Sandstone and coal beds are the major water-yielding units in the study area; shales do not yield water. Yields are as much as 610 L/min to wells penetrating thick saturated sections. However, average yields to most stock and domestic wells are less than 76 L/min. Where saturated, fractured clinker beds may yield as much as 250 L/min to wells.
Lebo confining layer	0-180	Includes Lebo Shale Member of Fort Union Formation—Predominantly dark shale interbedded with light-gray and brown to black carbonaceous shale, siltstone, and locally thin coal beds. Shales contain altered and devitrified volcanic ash and reddish-brown ferruginous concretions. White to light-gray argillaceous crossbedded and lenticular sandstones occur locally.	Relatively large percentages of lowly permeable shale in this unit retard vertical movement of water. However, in local areas where saturated, medium-grained channel sandstones may yield as much as 95 L/min to wells.

Table 18. *Hydrogeology of southeastern Montana--Continued*

Hydrogeologic Unit	Range of Thickness (m)	General Description	Water-Yielding Characteristics
Tullock aquifer	0-180	Comprises entire thickness of Tullock Member of Fort Union Formation and locally includes upper 3 to 24 m of Hell Creek Formation—Interbedded medium-gray to light-gray shale, light-gray fine-grained sandstone and siltstone, and thin but persistent coal beds. A resistant sandstone commonly forms a rimrock at the top of the unit. Locally, sandstones and siltstones weather yellow to brown.	Fine-grained sandstones and coal beds are the water-yielding units. Well yields may e as much as 150 L/min, but generally average about 57 L/min. Flowing wells tapping confined aquifers generally yield less than 38 L/min.
Lower Fort Union aquifer	0-170	Includes rocks in eastern part of study area equivalent to Lebo and Tullock Members of Fort Union Formation and may include uppermost part of Hell Creek Formation—Mostly interbedded light-gray to dark-gray shale, siltstone, and shaly sandstone. Upper part of unit is mostly shale; locally interbedded with lenticular siltstone and sandstone that commonly weather yellow to tan color. Lower part contains a few thin lignite coal beds. Overall appearance is darker than overlying and lighter than underlying units. Contact is conformable and generally transitional with underlying unit.	Shaly sandstones and coal beds are the water-yielding units. Typical well yields are 45 L/min. Locally, because of low permeability, the entire aquifer can retard vertical movement of water.
Upper Hell Creek confining layer	0-180	Comprises upper part of Hell Creek Formation—Gray to yellowish-gray silty clayey carbonaceous and bentonitic shale and siltstone; locally contains yellowish-gray to tan fine- to medium-grained silty sandstone, thin coal beds, and brown ferruginous concretions.	Limited as a water supply in the study area; a few flowing wells yield about 19 L/min. Generally a low permeability unit.
Fox Hills-Lower Hell Creek aquifer	0-230	Includes lower part of Hell Creek Formation and Fox Hills (Lennep) Sandstone—Gray to yellowish-gray to tan fine- to medium-grained sandstone; contains gray to olive-gray shale and shaly siltstone. Locally has massive or crossbedded sandstone layers and thin coal beds near top of unit. Lower contact considered to be the middle of the transitional siltstone located between sandstone above and shale of underlying unit. Contact is conformable with underlying unit.	Significant source of water in the study area. Yields 76 L/min to flowing wells along major streams valleys, where conditions permit. Yields as much as 260 L/min to domestic and stock wells and 760 L/min to municipal or industrial wells.
Bearpaw confining layer and older rocks, undifferentiated	0-340	Bearpaw confining layer consists of Bearpaw Shale and equivalent upper part of Pierre Shale; forms the base of the overlying shallow aquifer system—Bearpaw is gray to black marine shaly claystone and shale; thin beds of siltstone, silty sandstone, and bentonite occur locally.	Very low permeability; generally does not yield water to wells in the study area.